BIRLA CENTRAL LIBRARY
PILANI (Rajasthan)

Class No:- 620·7

Book No:- H14F

Accession No:- 45366

FOUNDATIONS FOR THE STUDY OF ENGINEERING

FOUNDATIONS FOR THE STUDY OF ENGINEERING

BY

G. E. HALL, B.Sc. (Manchester)

Associate of the Institution of Mechanical Engineers
Lecturer on Engineering at the Harris Institute, Preston
Author of " Mathematics for Technical Students "

WITH 153 ILLUSTRATIONS

Re-issue

LONDON
THE TECHNICAL PRESS LTD.
LATE OF AVE MARIA LANE, LUDGATE HILL
GLOUCESTER ROAD, KINGSTON HILL, SURREY
1947

PREFACE

IN preparing this work an attempt has been made to explain as simply as possible some everyday problems connected with the practical work of the young engineer.

(It is essential that the engineer should be a good practical worker and that he should be able to reason on scientific lines as to the why and the wherefore of the problems he meets. This state of affairs can only be reached if the young engineer has obtained a good grounding in elementary scientific principles, when he will be able to apply theory to practice.

The treatment of the subjects discussed will, it is hoped, serve as a foundation for further study of engineering problems in standard works and on which the student's career may be built up.

Too much emphasis cannot be given on the importance of being able to apply the principles and facts which have been learnt to the working out of numerical examples, and especially from the point of view of examinations. In order that the book may be produced at a reasonable price it has been necessary to limit the number of examples both in the text and at the ends of the chapters, but teachers using the book will be able to supplement those given when necessary.

In connection with some of the examples given, I should like to thank the Senate, University of London, the Joint Matriculation Board of the Northern Universities, and the Council of the Lancashire and Cheshire Union of Institutes for permission to reproduce questions from previous examination papers, such questions being marked L.M., N.M., and U.L.C.I. respectively.

My thanks are also due to the following for data supplied and for the loan of blocks or electros for some of the diagrams :—

Morris Oxford Press Ltd., Oxford (Fig. 72) ; Underfeed Stokers Ltd., London (Fig. 122) ; Messrs John Thompson, Wolverhampton (Figs. 123 and 124) ; Vacuum Oil Co. Ltd., London (Fig. 125), and to Messrs Tangye Ltd., Birmingham (Figs. 147 and 148).

G. E. H.

Harris Institute,
Preston.

CONTENTS

CHAPTER PAGE

I. VELOCITY AND ACCELERATION 1

II. FORCE AND THE LAWS OF MOTION . . . 20

III. WORK ENERGY AND POWER ENERGY TRANSMISSION 37

IV. ACTION OF FORCES ON BODIES AT REST. GRAPHIC STATICS 53

V. FRICTION AND LUBRICATION 73

VI. SIMPLE MACHINES AND MECHANISMS . . 85

VII. ELEMENTARY PROPERTIES OF ENGINEERING MATERIALS 104

VIII. MECHANICS OF FLUIDS 116

IX. THERMOMETRY. EFFECTS OF HEAT ON SOLIDS, LIQUIDS, AND GASES 133

X. MEASUREMENT OF HEAT. HEAT AND WORK. HEAT TRANSMISSION 155

XI. A FEW ESSENTIAL FACTS RELATING TO COMBUSTION 180

XII. THE STEAM BOILER 195

XIII. THE STEAM ENGINE 209

XIV. THE INTERNAL COMBUSTION ENGINE . . 235

ANSWERS TO THE NUMERICAL EXAMPLES . 253

INDEX 257

Foundations for the Study of Engineering

CHAPTER I

VELOCITY AND ACCELERATION

In olden days mechanics was the name given to the science which dealt with the making of machines, but now it is more generally applied to problems dealing with motion and with the action of forces on matter.

In this chapter we shall deal with the study of motion, which is simply change of position, without any reference to the forces which may be causing motion. Some writers refer to this particular branch of mechanics as the geometry of motion or " kinematics," and in solving problems we generally assume a particular point, called the origin, to be fixed.

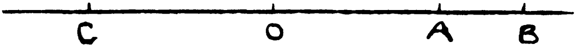


FIG. 1.

In Fig. 1, O represents some fixed point, and it is usual to denote such distances as OA and OB, measured to the right of O, as positive, the direction OC, measured to the left of O, being considered negative.

SPACE-TIME CURVE OR CURVE OF POSITIONS

Take two straight lines OX and OY intersecting at right angles at the point O (Fig. 2). Let OX represent time in hours and OY represent distance in miles, the point O being called the origin of reckoning for both time and distance.

Suppose that O represents a particular town and that a motorist leaves the town at 12 o'clock noon and travels uniformly at the rate of 20 miles an hour. At the point marked 1 on the time axis erect a perpendicular, and through

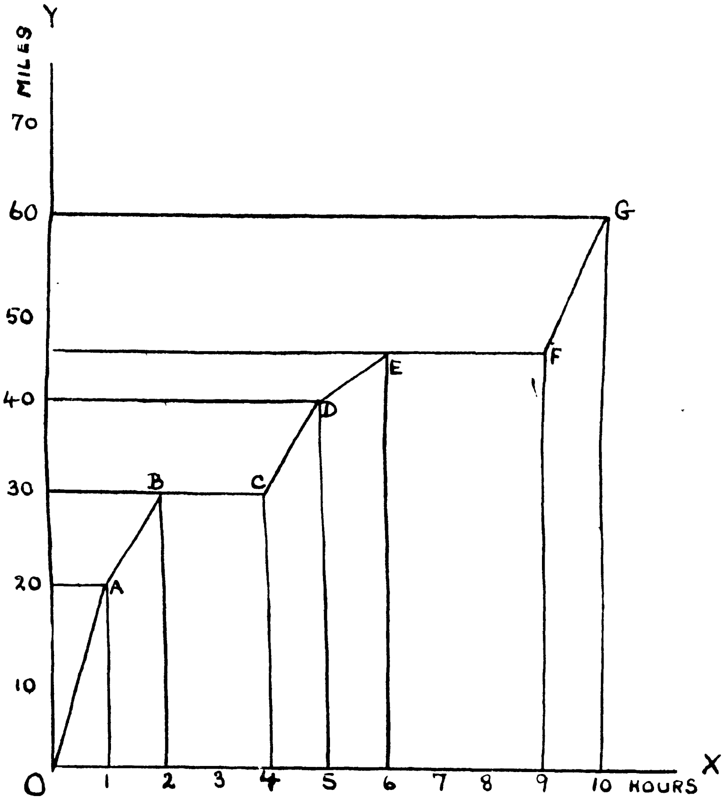


FIG. 2.

the point marked 20 on the distance axis draw a horizontal line cutting the perpendicular drawn from the point 1 at A, then A is the position of the motorist 1 hour after starting. During the next hour he travels uniformly at the rate of

10 miles an hour, so that B represents his position at 2 o'clock. If he now rests for 2 hours, at 4 o'clock he will still be 30 miles from his starting point, *i.e.*, C denotes his position. If we join the points ABC . . . obtained as in Fig. 2, we shall obtain a rough representation of his journey. Continuing a little further we find that between 4 and 5 o'clock he travelled at the rate of 10 miles an hour, between 5 and 6 o'clock he travelled 5 miles and rested at this point E, 45 miles from the starting point, until 9 o'clock. From our curve of positions we find that he finished his journey of 60 miles by travelling the last 15 miles in 1 hour.

RATE OF CHANGE OF POSITION

When any appropriate quantity is divided by a time we obtain a time rate. For example, if a body moves through 12 ft. in 4 secs., then in 1 sec. it will move through 3 ft., or, in other words, we say that the rate of change of position is 3 ft. per sec. The name given to rate of change of position, *i.e.*, the ratio $\dfrac{\text{distance travelled}}{\text{time taken}}$, is speed or velocity.

NOTE.—Any quantity which involves both a magnitude and a direction we call a *vector* or directed quantity, and rate of change of position should only be defined as velocity when the direction is known.

The total distance travelled by a moving body divided by the total time taken is known as the average speed of the body. If we know that a train travelled 60 miles in 1 hour we cannot say that it was moving with a uniform speed of 60 miles an hour, because in the course of an hour the speed may have varied. Neither can we say the speed is uniform if we know that it travelled 30 miles in half an hour, nor even if it travelled 1 mile in 1 min. If we reduced the interval of time to 1 sec. and we found that the train travelled 88 ft. each second for an hour, or, better still, if it was known to travel 8·8 ft. in each $\frac{1}{10}$ sec. for 1 hour, then we could say more truthfully that the train was travelling at a uniform speed. We can therefore say that a body is moving with a uniform speed or velocity if the distances travelled in equal intervals of time are equal *no matter how small these intervals may be.*

Let a body be moving in a given direction with a uniform velocity V ft. per sec., then in a time T secs. it will travel a distance S given by the formula $S=VT$ or from the definition of velocity $V=\frac{S}{T}$.

In a space-time diagram uniform velocity is represented by a straight line, as shown in Fig. 3. In this case let a body move from S_1 to S_2 in a small interval of time T secs., then velocity $V=\frac{S_2-S_1}{T}=\frac{AB}{CB}=\tan \underline{|ACB}$. Expressing this result in words, it means that in a space-time curve uniform velocity is represented by the gradient or the steepness of the line, the gradient being the tangent of the angle which the line makes with the time axis.

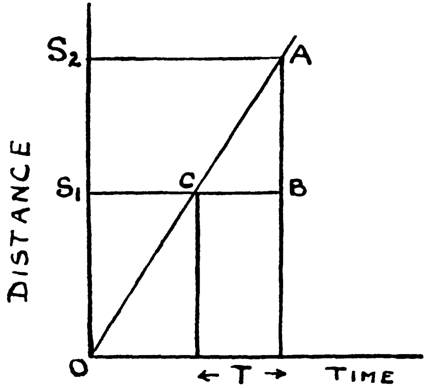


FIG. 3.

Fig. 4 shows a space-time curve for a body moving with a variable speed. In this diagram AB represents the total distance travelled in a time T, and $\frac{AB}{T}$ or $\frac{AB}{CB}=\tan \underline{|ACB}$, which means that in a space-time curve the average velocity is represented by the gradient of the chord joining the two points which correspond to the beginning and the end of the interval.

Example 1.—The average speed of a body during the first 4 secs. of its motion was 22 ft. per sec., and during the next 6 secs. it was 55 ft. per sec. What was the average speed for the whole time?

During the first 4 secs. it would travel $4 \times 22 = 88$ ft., and during the next 6 secs. it would travel $6 \times 55 = 330$ ft.

Total distance travelled $= 88 + 330 = 418$ ft.

Total time $= 10$ secs.

Therefore average velocity $= \frac{418}{10} = 41{\cdot}8$ ft. per sec.

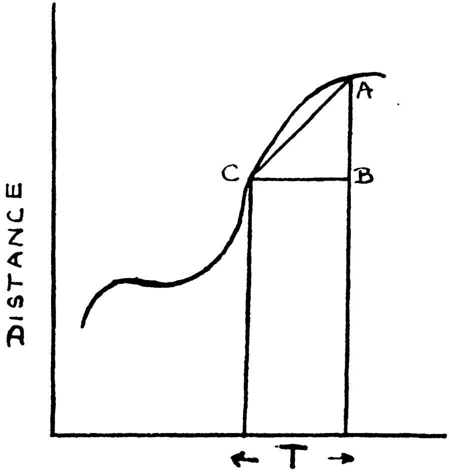


FIG. 4.

The reader will no doubt have noticed when travelling by train that his train and another may leave their respective platforms at the same time, and for a short distance they may be travelling in the same direction on parallel sets of rails. If the two trains are getting up speed at equal rates it would appear that the trains are stationary. If the other train is getting up speed at a greater rate than the one in which he is travelling, then he may obtain the impression that his train is at rest and that the other is moving forward. On the other hand, if his train is accelerating at the greater rate, then he sometimes obtains the impression that it is the other train which is moving backwards.

The rate at which one body is changing its position with regard to some other body is known as the relative velocity of the one with respect to the other. Actually all motion is relative, *i.e.*, the velocity of a body moving on the surface of the earth is relative to the earth, which, as you know, moves relative to the sun, which is moving relative to the stars. In this work, however, we will assume the earth to be at rest, so that we can speak of the actual velocity of a moving body.

In our calculations on the relative velocities of two trains there should be no difficulty if one of the trains is assumed to be stationary. If a train A is moving at 30 m.p.h. in one direction and another train B is moving at 40 m.p.h. in the opposite direction then the result is just the same as if A were at rest and B passed it at 70 m.p.h. We can therefore state that when two trains are travelling in opposite directions the relative speed of one with respect to the other is simply the sum of their respective speeds. By similar reasoning, when the trains are travelling in the same direction the relative speed of one with respect to the other is the difference between their respective speeds.

Example 2.—A train is 440 ft. long and travels at 15 m.p.h. Another train is 220 ft. long and travels at 30 m.p.h. How long will the trains take to pass one another (1) when travelling in opposite directions and (2) when travelling in the same direction ?

In Fig. 5, AB represents the train 440 ft. long and CD the

FIG. 5.

train of length 220 ft. Before the trains completely pass one another A will have to move through a distance equal to the sum of the lengths of the trains, *i.e.*, when travelling in either direction the total distance travelled when the trains have passed one another$=440+220=660$ ft.

(1) When travelling in opposite directions the relative velocity is $30+15=45$ m.p.h., or 66 ft. per sec., so that the time taken to pass one another$=\frac{660}{66}=10$ secs.

(2) When travelling in the same direction the relative velocity is 30—15=15 m.p.h., or 22 ft. per sec., so that in this case time taken$=\frac{660}{22}=30$ secs.

In Fig. 6, *abcd* represents the plan of a railway carriage compartment. Assume the train to be stationary and that a man enters the compartment at A. If he now walks across the compartment, then at the end of a certain interval of time he will arrive at the position C, *i.e.*, AC may represent his velocity across the compartment. Now suppose the train to be moving at such a speed that it travels to the position *a'b'c'd'* in the same time that the man takes to walk from A to C, *i.e.*, AB may represent the velocity of the train. At the end of the interval of time we are considering the man's position will be at D and the direction of his travel will be along AD. *In a diagram such as Fig. 6, AD is called the* resultant velocity, of which AB and AC are the components.

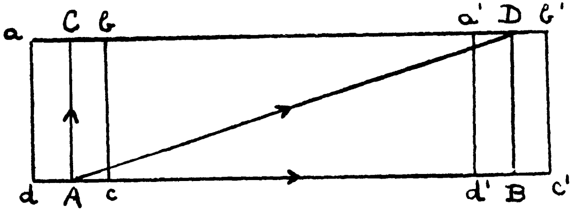


FIG. 6.

The above reasoning represents what is known as the "Parallelogram of Velocities," which states that if two velocities can be represented by two adjacent sides of a rectangle or parallelogram, drawn from a given point, then the resultant velocity will be represented by the diagonal of the rectangle or parallelogram *drawn from the same point.*

NOTE.—If we substitute forces for velocities in the above definition the result is known as the "Parallelogram of Forces," and if we substitute accelerations for velocities it is known as the "Parallelogram of Accelerations."

Readers will be able to solve problems on the parallelogram of velocities and forces quite easily by graphical methods, and those possessing a knowledge of elementary trigonometry will be able to verify their results by calculation, as shown by the following example.

Example 3.—Twelve miles an hour is the resultant of two velocities, one due east and the other due north. Find the northerly and easterly components when the resultant makes an angle of 30° with the easterly component.

Draw OE and ON perpendicular to one another, and from O draw OB at an angle of 30° to OE, making OB 12 units long to represent the resultant velocity, which is 12 miles an hour (Fig. 7).

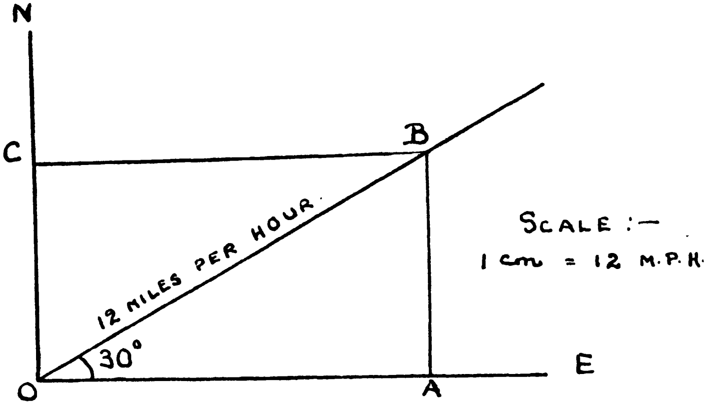


FIG. 7.

Complete the parallelogram (in this case a rectangle), and measure OA and OC.

To the same scale that OB represents 12 m.p.h. we find that OA=10·4 m.p.h. and OC=6 m.p.h.

Verifying these results by trigonometry we have

$$\frac{AB}{OB}=\sin 30^\circ,\ i.e.,\ \frac{AB}{12}=0{\cdot}5,$$

whence

$$AB=6 \text{ m.p.h.}$$

$$\frac{OA}{OB}=\cos 30^\circ,\ i.e.,\ \frac{OA}{12}=0{\cdot}866,$$

whence

$$OA=10{\cdot}392 \text{ m.p.h.}$$

Before proceeding further the reader should now test his knowledge of the subject by working out the solutions to questions 1 to 8 at the end of the chapter. Compare your results with the solutions given at the end of the book.

In our work so far we have considered rate of change of position, or the speed of a body, to be constant during any interval of time, and now we have to deal with problems in which the speed or velocity is not constant.

If the velocity of a body changes during a certain interval of time we can divide the change in velocity by the time and so obtain the rate of change of velocity, which we call the acceleration. The acceleration of a body is said to be uniform if the velocity changes by equal amounts in equal intervals of time, no matter how small these intervals may be.

Suppose that at a certain instant a body is moving at u ft. per sec., and T secs. later it is moving at V ft. per sec., then the change in velocity is $V-u$, and the rate of change of velocity or the acceleration $a=\frac{V-u}{T}$.

Note.—Since velocity may be measured in feet per second, and this is divided by time again in seconds, we have as our unit of acceleration feet per second per second, which is often written ft./sec.^{2}.

The above formula may be written as $V=u+aT$, and if the body starts from rest then it simply means that $u=O$. Given any three of the above four quantities we can use the relation to find the fourth, and if we are using the formula to find the acceleration of a moving body, and the acceleration turns out negative, it means that the body is being retarded.

Example 4.—At a certain instant a body is moving at 60 ft. per sec., and it is being retarded uniformly at the rate of 6 ft./sec. per second. When will it come to rest?

Substituting the given values in $V=u+aT$ in which T is required, we have

$$0=60+(-6)T, \textit{ i.e.}, -6T=-60,$$

whence

$$T=10.$$

The body will therefore come to rest in 10 secs.

Example 5.—Express an acceleration of 54,000 m.p.h. per hour in feet per second per second.

A velocity of 54,000 m.p.h. $=\frac{54000\times5280}{60\times60}=900\times88$ ft. per sec., and since this is gained every hour, the velocity gained per second will be $\frac{900\times88}{60\times60}=22$, *i.e.*, 54,000 miles per hour^2=22 ft./sec.^{2}.

The Velocity-time Curve.

This is a curve constructed with velocity on the vertical axis and time measured horizontally.

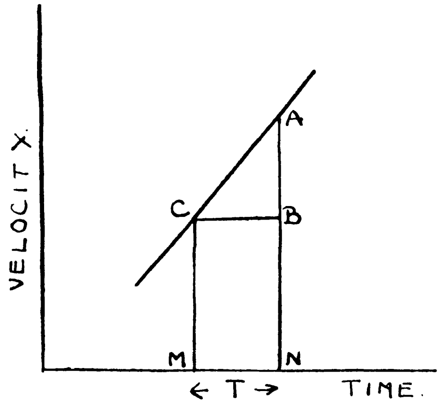


Fig. 8.

In Fig. 8 CM represents the velocity of a body at the instant M and AN represents the velocity at some later time N. Let this interval of time be denoted by T. The change in velocity is given by AB, and the rate of change of velocity is $\frac{AB}{T}$, *i.e.*, the acceleration is $\frac{AB}{CB}$ or tan $|$ACB. It will be easy to see that if the velocity is constant, *i.e.*, if there is no acceleration, then the graph will be a straight line parallel to the time axis.

If at a certain instant a body is moving at u ft. per sec., and T secs. later it is moving at V ft. per sec., then the average velocity during this time $=\frac{u+V}{2}$ ft. per sec., and if $S=$distance travelled in the T secs., then $S=\frac{u+V}{2}\,.\,T$. But we have already seen that the final velocity of a body V, moving with an initial velocity u, with constant acceleration a for a time T, is given by the formula $V=u+aT$. Substituting this value of V in the formula $S=\frac{u+V}{2}\,.\,T$, we have

$$S=\frac{(u+u+aT)}{2}\,.\,T,\ \textit{i.e.},\ S=\frac{(2u+aT)}{2}T=uT+\tfrac{1}{2}aT^2,$$

which relation we can use to find any one quantity if the others are known.

NOTE.—In the formula $S=uT+\frac{1}{2}aT^2$, if the body starts from rest, then $u=0$, so that $uT=0$, and therefore the formula becomes $S=\frac{1}{2}aT^2$.

Since $S=\frac{u+V}{2}\,.\,T$ and $a=\frac{V-u}{T}$, it will be possible to eliminate T by multiplying the two expressions together. Doing this we obtain

$$aS=\frac{(u+V)(V-u)T}{2T}=\frac{V^2-u^2}{2},\ \textit{i.e.},\ V^2-u^2=2aS,$$

which may be used to find the velocity acquired by a moving body after travelling a given distance with constant acceleration, no mention of the time being made.

NOTE.—In questions dealing with bodies falling under gravity we substitute $g=32$ ft./sec.^{2} for a in the above formulæ.

Example 6.—What distance will be travelled by a body in 5 secs. if it starts with a speed of 10 ft. per sec. and moves with a constant acceleration of 4 ft./sec.^{2} ?

In the formula $S=uT+\frac{1}{2}aT^2$ we have, substituting the known quantities,

$$S=10\times5+\tfrac{1}{2}\times4\times25,\ \textit{i.e.},\ S=50+50=100\text{ ft.}$$

Example 7.—How far will a body fall from rest in 10 secs. and what will be its speed at the end of that time ?

Using $S=\frac{1}{2}gT^2$, we have $S=\frac{1}{2}\times 32\times 100=1600$ ft. The final speed will be given by $V^2=u^2+2gS$, *i.e.*, $V^2=0+64\times 1600$, whence $V=\sqrt{64\times 1600}=8\times 40=320$ ft. per sec.

Example 8.—A body moves from rest with an acceleration of 32 ft./sec.². How far must it travel in order to attain a speed of 60 miles an hour?

60 miles an hour=88 ft. per sec. Therefore in the formula $V^2=u^2+2aS$ we have

$$88\times 88=0+64S, \text{ i.e., } S=\frac{88\times 88}{64}=12 \text{ ft.}$$

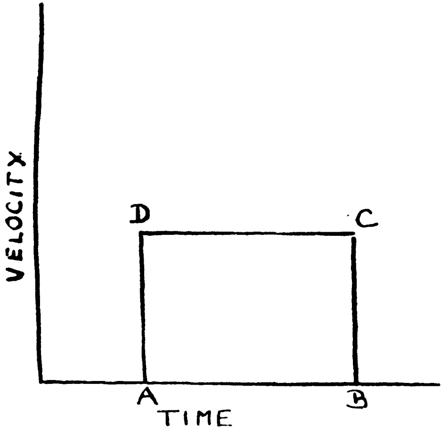


FIG. 9.

Returning to the velocity-time diagram it may now be shown that the space described by a moving body is represented by an area.

1ST CASE. *Constant Velocity.*—In Fig. 9 the velocity is constant and represented by the ordinate AD. In an interval of time AB the space described will be

$$\text{Velocity}\times\text{time}=AD\,.\,AB,$$

and this is obviously the area of the rectangle ABCD.

2ND CASE. *Variable Velocity.*—Let the velocity of our moving body vary during an interval of time represented by AB (Fig. 10).

Divide the interval during which the velocity changes into a large number of smaller intervals and complete the internal rectangles as shown. (In Fig. 10 we will consider three of these smaller intervals.)

Now suppose the velocity not to increase continuously, but to have during each of these small intervals a velocity it had at the beginning of that interval, then from our previous case in which the velocity was constant, it is easy to see that the total space described in the interval of time AB would be represented by the sum of all the internal rectangles. If, on the other hand, we assume the velocity to be equal to what it was at the end of the smaller intervals, then the space described would be represented by the sum of all the overlapping rectangles. If we make the number of these small intervals very large, then each will represent a very small interval of time, and the space actually described by the body will be greater than that represented by the internal rectangles, but it will be less than that represented by the overlapping rectangles. In other words, the space actually described by the moving body lies between these two areas and so does the boundary line of the curve. Therefore we can

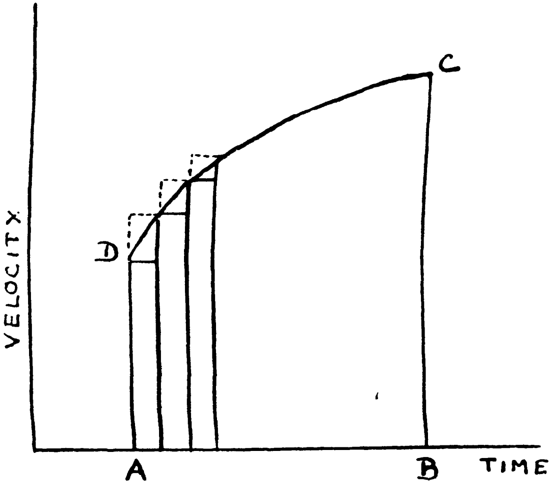


Fig. 10.

say that the space described is represented by the total area ABCD.

A similar argument will hold if the velocity decreases during a given interval. If the velocity sometimes increases and sometimes decreases, we consider separately the intervals during which it increases and those during which it decreases.

If a body is moving with uniform acceleration we can prove, from a velocity-time diagram, that the average velocity during any interval of time is equal to half the sum of the initial and final velocities, and it is also equal to the velocity at the middle of the interval.

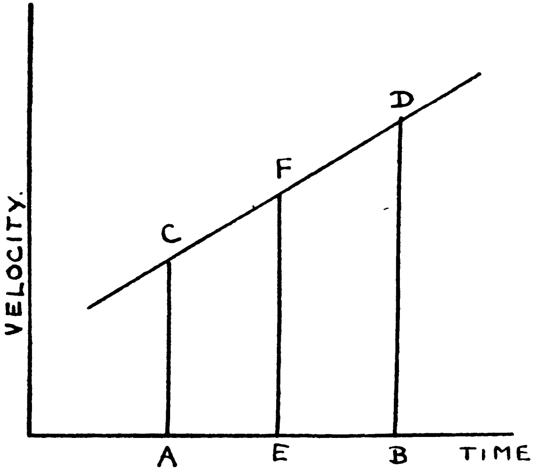


Fig. 11.

Consider Fig. 11.

Let AB represent a certain interval of time, AC equals the velocity of a body at the beginning of the interval, and BD equals the velocity at the end of the interval.

Bisect AB at E, and through E draw a vertical cutting CD at F.

$$\text{Space described} = \text{area of the trapezium ABDC}$$

$$= \text{FE} \,.\, \text{AB} = \frac{\text{AC}+\text{BD}}{2} \,.\, \text{AB}.$$

But $\frac{AC+BD}{2}$ is half the sum of the initial and final velocities, and EF is the velocity at the middle of the interval. Therefore the space described is the same as if the velocity had been constant and equal to each of these quantities during the interval AB.

Example 9.—A train starts from rest at one station, and its speed increases at a uniform rate until the maximum of 30 m.p.h. is reached. The speed then remains constant and the train passes through a station 4 miles from the starting point 10 mins. after starting. Determine the time taken to reach the maximum speed and the acceleration during that time.

Let the speed be increasing for a time T secs., then during this time the average speed will be $\frac{0+30}{2}=15$ m.p.h., or 22 ft. per sec., and the distance travelled during this time will be 22T ft. The train then runs for (600—T) secs. at its maximum speed and will travel (600—T)44 ft. The distance between the two stations is 4 miles, *i.e.*, 21,120 ft. Therefore we have

$$22T+(600-T)44=21120,$$

or
$$22T+26400-44T=21120,$$

or
$$-22T=-5280,$$

whence
$$T=240 \text{ secs.}$$

A speed of 44 ft. per sec. has been attained in 240 secs., therefore the acceleration $=\frac{44}{240}=\frac{11}{60}$ ft./sec.^{2}.

EXPERIMENT 1. *Velocity: Constant and Variable.*—Fletcher's trolley apparatus affords us a simple means of investigating rate of change of position and rate of change of speed.

It consists of a trolley which can run down a smooth plane (Fig. 12). A piece of paper is fixed on the top of the trolley, and on this paper a line is drawn by means of a brush dipped in ink and fixed to a vibrating rod, as shown.

When the vibrator is fixed in a certain position it makes a definite number of vibrations per second (in this case 5). The plane is tilted so that the trolley runs down at what you may consider a uniform speed, and as it runs down, the brush

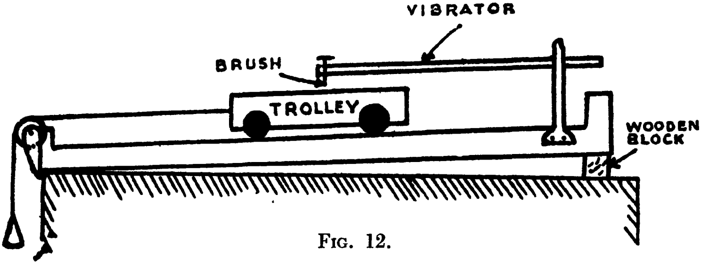


FIG. 12.

traces out a sinuous line, as shown in Fig. 13, the distances OA, AB, BC, etc., representing 0·2 sec., these points being on the centre line of the curve.

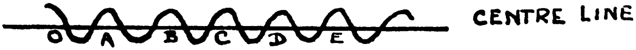


FIG. 13.

In an actual experiment the following results were obtained : OA=1·5 in., OB=3 in., OC=4·5 in., OD=6 in., OE=7·6 in. Tabulate these as follows :—

T.	S.	T.	S.
Sec.	In.	Sec.	In.
0·0	...	0·6	4·5
0·2	1·5	0·8	6·0
0·4	3·0	1·0	7·6

Plot S vertically and T horizontally and state conclusions.

When you have finished this part of the experiment fix a piece of string to the trolley, pass the string over a pulley, and suspend a small weight, as shown in Fig. 12.

In an experiment the weight suspended was 0·2 lb., and this caused a curve similar to that shown in Fig. 14.

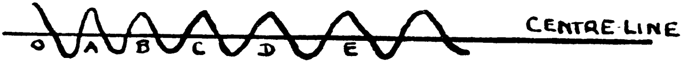


FIG. 14.

The following are the measurements obtained : OA=0·95 in., OB=2·45 in., OC=4·45 in., OD=7 in., OE=10·1 in.

Complete the following table :—

T.	S.	Increase in Distance.	Velocity V $=\frac{\text{Change in Distance}}{\text{Change in Time}}$.	Change in Velocity.	Acceleration $=\frac{\text{Change in Velocity}}{\text{Change in Time}}$
Sec.	In.				
0·0	...	...	...	...	...
0·2	...	...	...	...	...
0·4	...	...	...	...	...
0·6	...	...	...	...	...
0·8	...	...	...	...	...
1·0	...	...	...	...	...

Plot velocity and time and state conclusions.

NOTE.—Wherever possible the student should make simple pieces of apparatus for himself and actually perform the experiments which are described in this book. Many will obtain excellent results with the simplest of apparatus.

FIRST SET OF EXAMPLES

1. A and B are two towns 50 miles apart. A cyclist leaves A at 12 noon to meet a cyclist who leaves B at the same time. The cyclist leaving A rides at 10 m.p.h. for 2 hours and then rests for half an hour, after which he rides uniformly at 12 m.p.h. The cyclist leaving B rides uniformly at 5 m.p.h. Find, graphically, when and where they meet.

2. Define average velocity.

The distance between London and York is 188 miles, and a non-stop train does the journey in 3 hours 8 mins. What is the average speed of the train in miles per hour and in feet per second ?

3. A balloon is carried along by the wind at the rate of 22 ft. per sec. How long will it take to travel 1 mile ?

4. Define the parallelogram of velocities.

Find the resultant of two velocities, one of 20 m.p.h. and the other of 25 m.p.h. at an angle of 50° to the first.

5. A body moves at the rate of 12 ft. per sec. for 2 secs. For the next 3 secs. its speed is 22 ft. per sec., and then for

5 secs. it increases its speed to 30 ft. per sec. What is the average speed for the whole time?

6. A train travelling at 30 m.p.h. is brought to rest at a station in 2 mins. by applying the brakes. How far was the train from the station when the brakes were applied?

7. Explain carefully what is meant by the term relative velocity.

A train of length 884 ft. is travelling at 50 m.p.h. and passes a train of length 700 ft. travelling at 40 m.p.h. How long will they take to pass one another (1) if travelling in opposite directions, (2) if travelling in the same direction?

8. Two trains A and B are travelling in the same direction, and A is one and a half times as long as B. If the train B travelling at 45 m.p.h. passes A travelling at 30 m.p.h. in half a minute, what is the length of each train?

9. Explain the following terms :—

(*a*) Uniform velocity ; (*b*) average velocity ; (*c*) uniformly accelerated velocity ; (*d*) relative velocity.

A stone is thrown vertically upwards with a velocity of 20 miles an hour, how high does it rise? ($g=32$ ft./sec.^{2}.) N.M.

10. Express an acceleration of 81,000 m.p.h. per hour in feet per second per second, and an acceleration of 55 ft./sec.^{2} in yards per minute per minute.

11. Prove the formula $V^2=u^2+2gS$.

Through what height must a body fall in order to attain a speed of 45 miles an hour?

12. Explain what is meant by a velocity-time graph.

Draw the velocity-time graphs (*a*) for a body moving with a uniform velocity of 5 ft. per sec., (*b*) for a stone thrown vertically upwards with a velocity of 96 ft. per sec. ($g=32$ ft./sec.^{2}.) N.M.

13. Find, both in magnitude and direction, the resultant of two accelerations, one of 10 in./sec.^{2} in a vertical direction, and the other of 3,000 ft./min.^{2} in a direction inclined at an angle of 60° to the first. L.M.

14. A body moves with an acceleration of 10 ft./sec.^{2}. If the initial velocity is 12 ft. per sec., how far will it move in 10 secs.?

15. What is uniform acceleration?

If a body is moving with an acceleration of 15 ft./sec.^{2}, how long will it take to increase its speed from 30 to 45 ft. per sec.?

16. Prove graphically that if a body is moving with constant acceleration for a given interval of time, then the average velocity is the arithmetic mean of the initial and final velocities, and is also equal to the velocity of the body at the middle of the interval.

17. A train starting from rest at one station is at first uniformly accelerated until it attains its maximum speed of 60 m.p.h., which is then maintained uniform. The train runs through the next station, 5 miles from the first, 6 mins. after starting. Find the time taken to reach the maximum speed and the acceleration during this stage. L.M.

CHAPTER II

FORCE AND THE LAWS OF MOTION

It is difficult to give a very exact definition of force, but for our present purposes it may be sufficient to say that force is that which changes or tends to change a body's state of rest or motion. In this chapter we shall continue our study of motion, and in one or two simple cases we shall consider what force or forces may be causing motion, the name " kinetics " sometimes being given to this particular branch of our study.

If two forces act on equal masses for a given length of time and cause equal changes in velocity in these masses, then the two forces are said to be equal. It will be a matter of common experience to the student that different bodies, when acted on by equal forces for a given time, change their speeds at different rates, this difference in rate of change of speed being due to a difference in inertia or mass of the two bodies, and we customarily associate the idea of greater inertia with a slower rate of picking up speed when under the action of a given force.

Momentum is the name given to the product of the mass of a body and its velocity. The momentum which a given force is able to produce in a given time is a characteristic property of the force, because when the same force is applied to different bodies for a given time the velocities acquired in that time will be inversely proportional to the masses of the respective bodies, *i.e.*, the momentum is constant. We can therefore take as our unit of force that force which will produce unit momentum in unit time.

Units of Force

There will be two units in which a force may be measured, depending on whether we use the British (F.P.S.) or French (C.G.S.) system. In the former, unit force is defined as that force which when acting on a mass of 1 lb. for 1 sec. produces a velocity of 1 ft. per sec., the unit being known as the poundal. In the latter system, unit force is that which acts on a mass of 1 grm. for 1 sec. and produces a velocity of 1 cm. per sec. This unit is known as the dyne.

In the absolute system of units, since the attraction of the earth on a mass M units produces a velocity g in that mass every second, and therefore it produces a momentum Mg units, hence it is in absolute measure the gravity of a mass M. For example, the absolute measure of 1 lb.$=g$ poundals, and since g is approximately 32 ft./sec.^{2} therefore the British absolute unit of force$=\frac{1}{2}$ oz. (approx.). On the metric system $g=980$ cm./sec.^{2} roughly, so that the dyne is about $\frac{1}{1000}$ grm.

In measuring forces the engineer uses what is called the gravitational system. In this case the force is measured by the mass it would support against gravity ; for example, in the British system a force of 10 lbs. would be defined as the force which a mass of 10 lbs. exerts on whatever may be supporting it when at rest.

In the absolute system the attraction of the earth on a mass m is mg, and on a mass M it is Mg, these being proportional so long as g is constant. Therefore we can see that forces which are equal on the absolute system are also equal on the gravitational system if the measurements are made at the same place. If, however, the forces are measured in terms of gravity at different places, the results will not be quite constant, owing to the slight variations in the value of g due to the fact that the earth is not a perfect sphere. For this reason in scientific work where very great accuracy is required we use the absolute unit of force, but, as already mentioned, for all practical purposes the engineer uses the everyday gravitational unit.

The above remarks supply us with definitions of mass and weight. The mass of a body we define simply as the quantity of matter it contains, but the weight of a body is the force with which it is attracted towards the centre of the earth. (A 1-lb. mass and a 1-lb. weight are not always equal. An ordinary balance compares masses, a spring balance measures weight.)

THE FUNDAMENTAL EQUATION OF DYNAMICS

We have seen that the force acting on a body is proportional to the mass of the body and to the rate of change of speed or acceleration produced. Let F=force, m=mass, and a=acceleration, then F : : ma, or we can say that F=Kma where K is a constant. If, then, our unit of force is that force which gives unit acceleration to unit mass, we have 1=K . 1 . 1, *i.e.*, K=1, and therefore we have the most important result, $F=m\ .\ a$.

NOTE.—In the above form F is measured in poundals. Expressing F in pounds, we have

$$F=\frac{ma}{g}.$$

Example 1.—A force of 12 lbs. acts on a mass of 4 lbs. What is the acceleration produced ?

$$F=\frac{ma}{g},\ i.e.,\ 12=\frac{4a}{32},$$

whence $a=96$ ft.-sec.^{2}.

EXPERIMENT 2. *To show that the Force is Proportional to the Acceleration, the Mass being Constant.*—Use the Fletcher trolley, as in the second part of Experiment 1, but place four separate 0·1-lb. weights on the front of the trolley so as not to interfere with the action of the brush. Attach a 0·1-lb. weight to the pulling cord, leaving the other three weights on the trolley. Obtain a curve as shown in Fig. 14. Now place two 0·1-lb. weights on the pulling cord, leaving the other two on the trolley. Obtain another curve. Lastly, place three 0·1-lb. weights on the cord, leaving one on the trolley, and obtain another curve.

In an experiment three curves were obtained similar to that shown in Fig. 14, the following measurements being noted :—

1st Curve. Pulling force, 0·1 lb.
OA=0·6″, AB=0·9″, BC=1·15″, CD=1·45″, DE=1·7″.

2nd Curve. Pulling force, 0·2 lb.
OA=0·85″, AB=1·3″, BC=1·8″, CD=2·3″, DE=2·75″.

3rd Curve. Pulling force, 0·3 lb.
OA=1·0″, AB=1·75″, BC=2·45″, CD=3·1″, DE=3·8″.

NOTE.—Each distance given above represents 0·2 sec. Obtain the average acceleration in each case, then plot pulling force vertically and acceleration horizontally. State conclusions.

RATE OF CHANGE OF MOMENTUM

Suppose a body of mass M to be moving at u ft. per sec., then its momentum$=$Mu. If after a time T secs. the velocity increases to V ft. per sec., then the momentum will increase to MV. Change in momentum$=\mathrm{MV}-\mathrm{M}u$ or $\mathrm{M}(\mathrm{V}-u)$, and the rate of change of momentum$=\mathrm{M}\frac{\mathrm{V}-u}{\mathrm{T}}$. But $\frac{\mathrm{V}-u}{\mathrm{T}}=a=$acceleration, therefore rate of change of momentum $=\mathrm{M}a$, or, expressing it in words, we can say that rate of change of momentum is equal to the applied force.

NOTE.—The unit of momentum is sometimes called the poundem on the F.P.S. system and the bole on the C.G.S. system.

Example 2.—What momentum will be produced in a mass of 10 lbs. which has fallen freely from rest through a distance of 81 ft.?

The velocity acquired after falling through 81 ft. will be given by $\mathrm{V}^2=2g\mathrm{S}$, *i.e.*, $\mathrm{V}^2=64\times 81$, and therefore

$$\mathrm{V}=\sqrt{64\times 81}=72 \text{ ft. per sec.}$$

$$\text{Momentum}=\text{mass}\times\text{velocity}=10\times 72=720 \text{ units.}$$

Consider the formula $\mathrm{F}=\mathrm{M}a$. Multiplying both sides by time T we have

$$\mathrm{FT}=\mathrm{M}\,.\,a\,.\,\mathrm{T}, \text{ or } \mathrm{FT}=\mathrm{M}\left(\frac{\mathrm{V}-u}{\mathrm{T}}\right)\mathrm{T}=\mathrm{M}(\mathrm{V}-u).$$

In words this result means that change of momentum can be given by the product force × time, which product is known as the impulse of the force. Obviously the smaller the time during which the force acts the greater the impulse, and that is why a sharp blow from a hammer is more effective in driving a nail into a piece of wood than a steady pressure applied at the nailhead.

IMPACT

In the case of an impact the velocity of a body is changed in a very short interval of time, and therefore the average force during that interval, since it is measured by rate of change of momentum, must be very great. Although during an impact the interval of time is small, we can conclude that the force is not uniform, but increases from zero to a maximum and finally falls again to zero.

Consider what happens when a billiard ball A strikes another one B. At every instant during contact the force which B exerts on A is exactly equal and opposite to that which A exerts on B. In other words, this means that the momentum gained by one ball is exactly equal and opposite to the momentum lost by the other, the total momentum of the two being constant.

Let M_1 and M_2 be the masses of A and B respectively, u_1 and u_2 be their velocities before impact, and V_1 and V_2 be their velocities after impact, then we have

$$M_1V_1+M_2V_2=M_1u_1+M_2u_2,$$

from which we can find any one quantity if the remaining quantities are known.

NOTE.—In this work we assume both bodies to be perfectly elastic, which means that the relative velocity before impact is equal to the relative velocity after impact. As the student continues his study of mechanics he will find that the relative velocity after impact is less than the relative velocity before impact, the ratio between these two being called the coefficient of restitution.

Example 3.—A ball of mass 5 lbs. is moving at 6 ft. per sec. and strikes a ball of mass 8 lbs. moving in the same direction at 5 ft. per sec. If after the impact the smaller ball comes to rest, what will be the final velocity of the larger one ?

Total momentum before impact=total momentum after impact, *i.e.*, $M_1u_1+M_2u_2=M_1V_1+M_2V_2$, therefore substituting we have

$$5\times6+8\times5=5\times0+8V_2, \text{ or } 30+40=0+8V_2,$$

whence $V_2=8{\cdot}75$ ft. per sec.

Sir Isaac Newton (1642-1727) laid the foundation for all our achievements in physical science, astronomy, and engineering when he stated what are now known as Newton's Laws of Motion, which are as follows :—

First Law.—Every body will continue in its state of rest or of uniform motion in a straight line except when some force or forces cause it to change that state.

Second Law.—Rate of change of momentum is proportional to the applied force and takes place in the same straight line as that in which the force acts.

Third Law.—Action and reaction are equal and opposite.

Many everyday phenomena could be mentioned which verify the truth of these laws, but it will be better for the student to think of these for himself.

Our next consideration will be a brief study of circular motion and of the forces which act on a body when rounding a curve.

A radian is defined as the angle at the centre of a circle which stands on an arc equal in length to the radius, and it is left as an exercise for the student to prove that $360° = 2\pi$ radians. The student should also know that the radian measure of an angle is the ratio $\frac{\text{arc}}{\text{radius}}$.

Our unit of angular velocity is one radian per second, denoted by ω, and we have to be able to express angular velocity in terms of the linear speed round the circumference of a circle.

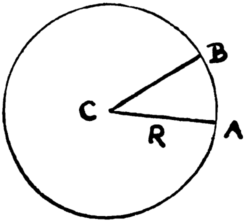


FIG. 15.

In Fig. 15 C is the centre of a circle of radius R, and suppose a body moves round the circumference with a uniform angular velocity ω radians per sec. If the linear speed of the body moving round the circumference is V ft. per sec., then when it has moved through an arc AB=S ft. it will have turned through $\frac{S}{R}$ radians, and the time taken will be $\frac{S}{V}$ sec.

$$\text{Therefore angular velocity } \omega = \frac{\text{angle turned through in radians}}{\text{time taken}}$$

$$= \frac{S}{R} \div \frac{S}{V} = \frac{S}{R} \cdot \frac{V}{S} = \frac{V}{R} \text{ radians per sec.,}$$

i.e., the angular velocity is the linear speed of the body divided by the radius of the circle, or we may say $V=\omega R$.

The unit of angular acceleration is 1 radian/sec.^{2}. Again referring to Fig. 15, suppose that the angular velocity of a body moving round the circumference of the circle is ω_1 radians per sec. when the body is at A, and ω_2 radians per sec. when at B. If this change in angular velocity takes place in a time T secs., then the angular acceleration $A=\frac{\omega_2-\omega_1}{T}$ radians/sec.^{2}.

If V_1=linear speed of the body when at A, and V_2=linear speed when at B, then we have

$$\omega_2=\frac{V_2}{R} \text{ and } \omega_1=\frac{V_1}{R},$$

i.e., angular acceleration$=\frac{V_2-V_1}{RT}$,

but $\frac{V_2-V_1}{T}$=linear acceleration a.

Therefore angular acceleration $A=\frac{a}{R}$, or $a=AR$.

Example 4.—A train runs round a curve 20 chs. radius at a speed of 30 m.p.h. What is the angular velocity in radians per second? (1 ch.=66 ft.)

Radius of curve $R=20\times 66=1320$ ft.

30 m.p.h.=44 ft. per sec.

Therefore angular velocity $\omega=\frac{V}{R}=\frac{44}{1320}=\cdot 0333$.

Example 5.—Find the angular acceleration of a point on the rim of a flywheel which increases its speed from 550 to 690 revs. per min. in 55 secs.

Increase in revolutions per minute in 55 secs.$=690-550$ $=140=\frac{140}{60\times 55}$ revs./sec.^{2}, and since 1 rev.$=2\pi$ radians angular acceleration in radians per second per second

$$=\frac{140\times 44}{7\times 60\times 55}=0\cdot 266.$$

Vector Addition and Subtraction

A vector is a straight line, such as AB (Fig. 16), which has a definite magnitude and direction, and any two vectors having the same magnitude and direction, such as AB and CD, are said to be equal.

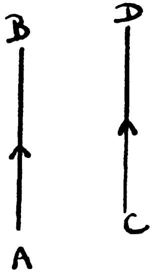


Fig. 16.

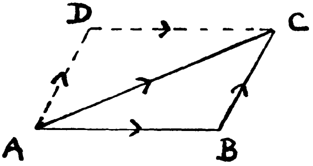


Fig. 17.

To add together two vectors P and Q draw AB to represent P in magnitude and direction, and draw BC to represent Q, then the vector AC is said to be the sum of P and Q, and will be denoted by $P+Q$. Completing the parallelogram ABCD (Fig. 17) we have

$$\overrightarrow{AD}+\overrightarrow{DC}=\overrightarrow{AC}, \textit{ i.e., } Q+P=P+Q.$$

The minus sign prefixed to a vector simply means that its sense is to be reversed, so that $-\overrightarrow{AB}=\overrightarrow{BA}$.

Draw $AB=P$ and $BC=Q$ (Fig. 18), and draw $BC'=-Q$. We have

$$P-Q=AC', \ P-Q+Q=\overrightarrow{AC'}+\overrightarrow{BC}=\overrightarrow{AC'}+\overrightarrow{C'B}=\overrightarrow{AB}=P.$$

It has already been stated that velocity is a vector or directed quantity, and that being the case any change in direction must necessarily mean a change in velocity. We can now state that which often causes confusion with beginners because they do not realise that a change in direction means a change in velocity, and that is that a body moving with a uniform speed round the circumference of a circle *must have an acceleration.*

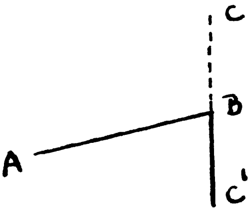


Fig. 18.

A body moves round the circumference of a circle radius R ft. with a constant speed V ft. per sec. To prove that the acceleration $a=\frac{V^2}{R}$.

At a certain instant suppose the moving body to be at a point A, and after T secs. suppose it arrives at B (Fig. 19). There has been a change in direction, and we can find this change by the method of vector addition explained above.

Draw *ca* to a convenient scale to represent the speed of the body when at A, both in magnitude and direction. Also from *c* draw *cb* to represent the speed at B. The magnitude of *cb* will be the same as *ca*, but its direction will be different.

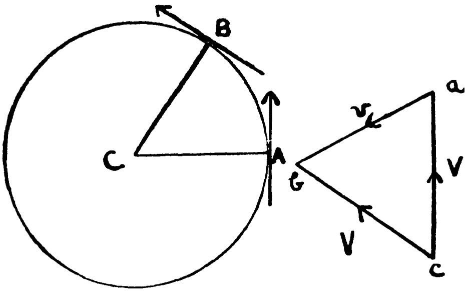


FIG. 19.

By the addition of vectors we can state that *ab* represents the change in velocity which occurred in moving from A to B, say *v*.

Now assume that A and B are very close together, then for all practical purposes we can state that the triangles CAB and *cab* are similar, and from the properties of similar triangles we have

$$\frac{v}{V}=\frac{AB}{R}.$$

Now AB=distance travelled by a body in T secs. when moving at V ft. per sec.=VT.

Therefore $$\frac{v}{V}=\frac{VT}{R},\ \textit{i.e.},\ \frac{v}{T}=\frac{V^2}{R}.$$

But $\frac{v}{T}$=rate of change of velocity=acceleration, *i.e.*, acceleration $a=\frac{V^2}{R}$ towards the centre of the circle.

Example 6.—A small weight is attached to the end of a string 3 ft. 6 in. long, and is whirled round at a speed of 180 revs. per min. Calculate the acceleration of the stone.

180 revs. per min.=3 revs. per sec.

$$\text{Circumference of circle}=\frac{22}{7}\times 7=22 \text{ ft.}$$

Therefore speed of the stone=$22\times 3=66$ ft. per sec.

$$\text{Acceleration}=\frac{V^2}{R}=\frac{66\times 66}{3{\cdot}5}=1244\tfrac{4}{7} \text{ ft./sec.}^2.$$

CENTRIFUGAL FORCE

Fig. 20 shows a small mass *m* attached to a string and whirled round in a circle centre *c* and radius R ft. At every point along the circumference of the circle the mass is travelling in a direction tangential to the circle, and if the string were to break, the mass would "fly off at a tangent."

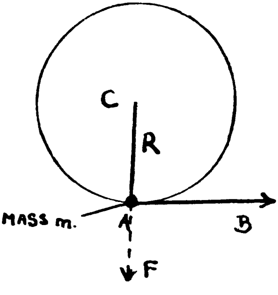


FIG. 20.

It is common experience that when a mass is whirled round in a circle a force, denoted by F in Fig. 20, is always acting and tending to cause the mass to leave its support *c*. According to Newton's third law there is another force equal in magnitude and opposite in direction to F which makes the mass keep to its circular path. The force acting inwards towards the centre of the circle is called the centripetal force. The force acting outwards tending to make the mass leave its circular path is called centrifugal force.

The student should be familiar with many cases in which centrifugal force plays a part, as, for instance, the bursting of the rim of a flywheel when its speed is excessive.

To find the centrifugal force acting on a mass m which is rotating in a circle radius R at V ft. per sec.

Consider the formula $P=ma$.

In the case of circular motion we have shown that $a=\frac{V^2}{R}$, therefore $P=m\frac{v^2}{R}$ absolute units, or $P=\frac{mV^2}{gR}$ gravitation units.

This relation gives the centrifugal force if acting outwards or the centripetal force if acting inwards.

Example 7.—Calculate the centrifugal force in pounds acting on an aeroplane weighing 2,000 lbs. when rounding a curve 200 ft. radius at 60 m.p.h.

$$P=\frac{mV^2}{gR}.$$

Substituting the known values in this formula we have

$$P=\frac{2000\times88\times88}{32\times200}=2420 \text{ lbs.}$$

SUPERELEVATION OF RAILWAY LINES

The student will have observed that tramcars, motor cars, and other vehicles, unless they are already moving very slowly, slow down when turning from one street into another. If the vehicle continued to move at a high speed when rounding a curve it would overturn, owing to the action of various forces. For example, the diagram (Fig. 21) represents a car which is rounding a curve. The forces acting are F_1, F_2, and F_3. The force F_1, acting inwards, is that due to the action of the rails on the wheels, and F_2 represents the centrifugal force acting outwards. These two forces constitute an overturning moment (for definition of moment of a force see Chapter IV.), and F_2 has to be balanced by a force F_3, as shown. For slow-moving vehicles the overturning moment is small, and when it does act it can always be reduced by reducing the speed.

In the case of a railway train considerable delay and inconvenience would be caused if the train had to reduce its speed every time it travelled round a curve, so in order to overcome the difficulty the railway engineer raises the outer rail above the inner, *i.e.*, he gives the rails what is called a superelevation or cant.

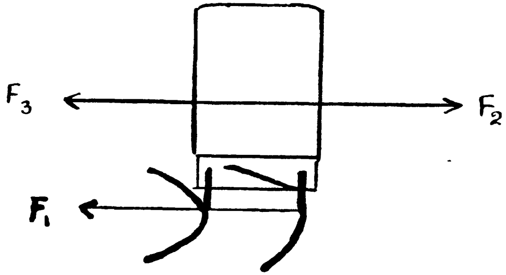


Fig. 21.

To determine the superelevation.

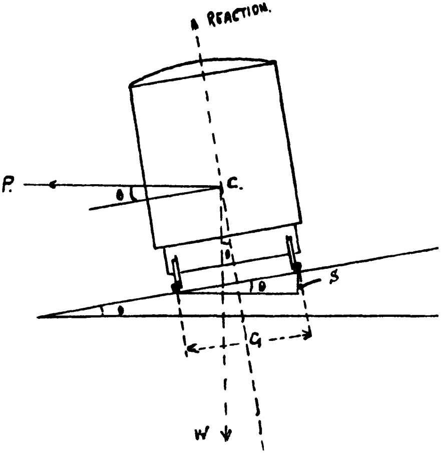


Fig. 22.

Let W=weight of train, V=speed in feet per second, R=radius of curve in feet, G=gauge (the standard gauge for British railways is 4 ft. 8½ in.), θ=angle of cant.

Consider Fig. 22.

The weight of the train W acts vertically downwards, the reaction of the rails being perpendicular to the plane containing them. The force F acts horizontally towards the centre of the curve, and by geometry the student should prove that the angles marked θ are all equal.

Resolving the forces which are acting in a direction parallel to the slope of the track we have

$$W \sin\theta = F \cos\theta, \text{ or } \frac{F}{W} = \frac{\sin\theta}{\cos\theta} = \tan\theta.$$

But we know that $F=\frac{MV^2}{R}$ (absolute units) and that $W=M \cdot g$, therefore we have

$$\tan \theta=\frac{MV^2}{MgR}=\frac{V^2}{gR},$$

from which we can find the slope in degrees.

If S = the required superelevation, we have from the diagram

$$\frac{S}{G}=\sin \theta, \text{ or } S=G \sin \theta.$$

If you now refer to your trigonometrical tables you will notice that $\sin \theta=\tan \theta$ when θ is small, and it is in the case of a railway slope, so that we can write

$$S=G \tan \theta=\frac{GV^2}{gR} \text{ ft., or } \frac{12GV^2}{gR} \text{ in.}$$

From this relation we can determine any one quantity if the others are known.

Example 8.—Determine what superelevation must be given to the outer rail of a standard gauge railway in order that a train may travel round a curve half a mile radius at a speed of 45 m.p.h. without side thrust between the rails and wheel flanges.

If θ = angle of cant, then

$$\tan \theta=\frac{V^2}{gR}=\frac{66 \times 66}{32 \times 2640}=0{\cdot}051.$$

$$\text{Superelevation}=\text{gauge} \times \tan \theta=56{\cdot}5 \times 0{\cdot}051=2{\cdot}88 \text{ in.}$$

SIMPLE HARMONIC MOTION

This we define as the projection of a uniform circular motion on to the diameter of a circle, and it is of great importance to the engineer since many of the motions with which he has to deal are simple harmonic or very close approximations. In this work we need only consider one or two simple cases, a detailed study of the subject being postponed until a later stage.

Consider Fig. 23. Here OA represents a crank which rotates round a point *o* in the direction of the arrow. The projection of A on the diameter DD′ is at B, and as A rotates from the position D round the circle and back to D, B will move along the diameter from D to D′ and back to D, *i.e.*, the motion of B is simple harmonic.

Consider a suspended spring, as shown in Fig. 24. From the end of the spring suspend a weight W. Displace W through a distance *d*. Release the weight, then the spring will move upwards and downwards, *i.e.*, the weight W will have a simple harmonic motion.

Again referring to Fig. 23, if A rotates round the circumference of the circle radius R uniformly at V ft. per sec., then the acceleration of A will be $\frac{V^2}{R}$, and the acceleration of B will be

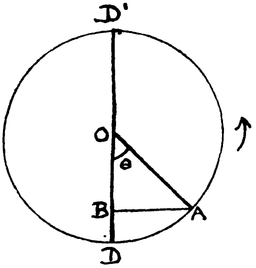


FIG. 23.

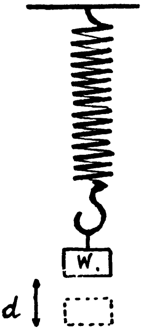


FIG. 24.

$$\frac{V^2}{R}\cos\theta=\frac{V^2}{R}\cdot\frac{OB}{R}=\frac{V^2}{R^2}\cdot OB,$$

i.e., the acceleration of any point $=\frac{V^2}{R^2}$ displacement.

Therefore we have

$$\frac{V^2}{R^2}=\frac{\text{acceleration}}{\text{displacement}},$$

or, taking the square root of both sides and reversing,

$$\frac{R}{V}=\sqrt{\frac{\text{displacement}}{\text{acceleration}}}.$$

Time T secs. to make one complete revolution at V ft. per sec.

$$=2\pi\frac{R}{V},\ i.e.,\ T=2\pi\sqrt{\frac{\text{displacement}}{\text{acceleration}}}.$$

Since $P=\frac{ma}{g}$ we have

$$\text{acceleration}=\frac{\text{force}}{\text{mass}}=\frac{\text{force}\ g}{W}.$$

Therefore $$T=2\pi\sqrt{\frac{\text{displacement}\,.\,W}{\text{force}\,.\,g}},$$

and force may be measured as that per foot of displacement.

EXPERIMENT 3. *Vibration of a Spring.*—Measure the length of the spring shown in Fig. 24 between the end coils. Suspend 0·5 lb. from the end and measure the extension. Increase the weight 0·5 lb. at a time until 2 lbs. have been added. Plot a load extension diagram, *i.e.*, load vertically and extension horizontally. From your graph find the force per foot of displacement, or, as it may be called, the stiffness of the spring. Set the spring vibrating and note the time for 50 complete vibrations, then find the periodic time T, *i.e.*, the time of 1 vibration.

The following are the results of an experiment :—

Load (lbs.) . .	0	0·5	1·0	1·5	2·0
Extension (inches) .	0	0·35	0·7	1·25	1·7

The spring made 50 vibrations in 22·5 secs.

Complete the table shown, and in the last column calculate the value of g.

Load. W.	Force/Foot Displacement.	Time of 50 Vibrations.	Periodic Time T.	$T=2\pi\sqrt{\frac{W}{\text{Force/Foot}\,.\,g}}$.
Lbs. 2	...	Secs. 22·5	...	...

EXPERIMENT 4. *Simple Pendulum.*—Attach a small weight to the end of a piece of string, the length of which can be varied. Cause it to vibrate as a pendulum and note the time

in seconds of 10 complete swings. Calculate the periodic time T for different lengths L.

In an experiment the following results were obtained :—

L.	Time of 10 Swings.	Periodic Time T.	T^2.	$\frac{L}{T^2}$.
Ft.				
0·5	8·0	...	...	...
1·0	11·0	...	...	...
1·5	13·5	...	...	...
2·0	15·5	...	...	...
2·5	17·5	...	...	...
3·0	19·5	...	...	...

Complete the last three columns and state the relation between L and T^2.

Take any of the above lengths and calculate the value of g from the relation $T=2\pi\sqrt{\frac{L}{g}}$.

Do the above calculated values of g differ very much from 32 ft./sec.^{2}? If so, can you account for the difference?

SECOND SET OF EXAMPLES

1. Distinguish between the absolute and gravitational units of force. For how long must a force equal to the weight of 2 grm. act on a body originally at rest to produce in it 39,200 C.G.S. units of momentum? ($g=980$ cm. per sec.^{2}.) N.M.

2. Describe an experiment by means of which you could find the value of g.

3. What is the effect produced by a force on the motion of a body? Define the dyne and the poundal. L.M.

4. State the relation which expresses the resultant force on a body in terms of the mass and the acceleration of the body. *Account for the apparent variations in his weight* which a man feels at the initial and final stages of a journey in a lift. L.M.

5. Define momentum. Find the increase in momentum produced in a body when a resultant force of 100 dynes acts

upon it for 6 secs. If during this time the velocity increases by 20 cm. per sec., what is the mass of the body? L.M.

6. State Newton's second law of motion.

Use it to explain the derivation of the unit force in the foot-pound-second system of units.

Given that 1 lb.=453·6 grm., how would you convert poundals in the above system of units into "dynes" in the C.G.S. system? U.L.C.I.

7. A motor car weighs 24 cwt., of which two-thirds is carried by the rear wheels. The car is travelling on a level road at 35 m.p.h. when the brakes, which are fitted to the back wheels, are suddenly applied and lock the wheels. The coefficient of friction between the tyres and road is 0·65.

Find (*a*) the momentum of the car at 35 m.p.h., (*b*) the time taken in bringing the car to rest. U.L.C.I.

8. Calculate the centripetal force required to keep a mass of 10 lbs. revolving in a circle 7 ft. diameter at 60 revs. per min.

9. Calculate the length of a pendulum whose periodic time is 2 secs. ($g=32$ ft./sec.^{2}.)

10. Distinguish between the mass of a body and its weight.

When a body is weighed at the earth's surface on an ordinary balance and on a certain spring balance, it is found that the readings agree. Describe and explain the difference that would be found between similar weighings taken in a balloon. N.M.

11. Without assuming a formula, find the maximum permissible speed in miles per hour of a train when running over a curve of 600 ft. radius, the gauge being 4 ft. 8½ in., and the cant or superelevation 6½ in. U.L.C.I.

12. A motor car of 1 ton weight goes round a corner of radius 20 yds. at a speed of 15 miles an hour. Find the horizontal force towards the centre of the curve which is necessary to enable it to do this, and state how it is supplied. N.M.

CHAPTER III

WORK ENERGY AND POWER ENERGY TRANSMISSION

THE terms " force " and " work " when used in mechanics have definite meanings, and the student must be able to distinguish between the terms and give each its correct meaning. If you lift a weight vertically from the floor through a given distance you will be doing work, and if you then continue to support the weight at the height to which you have raised it, you will not be doing work but simply exerting a force. A force, then, acting on a body and causing the body to move through a distance, does work, the unit being the foot-pound, *i.e.*, when you lift a 1-lb. weight vertically through 1 ft. you are said to perform 1 ft.-lb. of work.

Sometimes a force may not be acting in a direction parallel to the motion, as shown in Fig. 25. In this case suppose a force F acts at an angle θ to the direction of motion, then the work done will be defined as the product of the displacement and the orthogonal projection of the force upon it, *i.e.*, work done=SF cos θ. In a case such as this it will be noticed that if $\theta=90°$, then the work done will be zero, and if θ is greater than 90°, then the work must be considered negative.

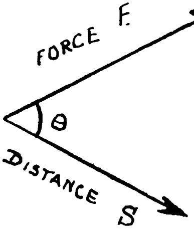


FIG. 25.

Example 1.—A force of 10 lbs. acts on a body in a direction parallel to the motion and causes it to move through 50 ft. How many foot-pounds of work will be done? Calculate the work done when the force acts at an inclination of 60° to the direction of motion.

In the first case, work done=force×distance=10×50 =500 ft.-lbs.

In the second case, work done=force × cos 60° × distance =10 × 0·5 × 50=250 ft.-lbs.

The amount of work done when a force of 1 lb. acts through a distance of 1 ft., *i.e.*, the foot-pound is known as the practical unit and is that adopted by the engineer. There are occasions, however, when we may wish to use the absolute unit of work, which in the F.P.S. system is the foot-poundal, *i.e.*, the work done when a force of 1 poundal acts through a distance of 1 ft. In the C.G.S. system the absolute unit of work is known as the erg, and this is the work done when a force of 1 dyne acts through a distance of 1 cm.

NOTE.—1 practical unit of work=g absolute units.

To prove that the work done by two forces is equal to the work done by their resultant.

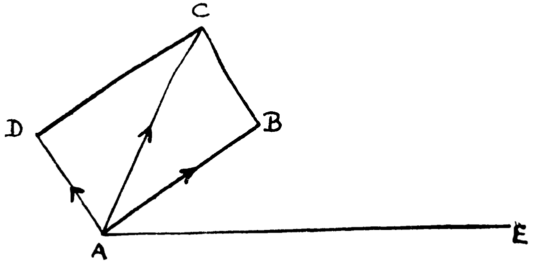


FIG. 26.

Let AB and AD represent two forces of which AC is the resultant, the displacement being represented by AE (Fig. 26).

The work done by AB and AD will be AE (projection of AB along AE)+AE (projection of AD along AE)=AE (projection of AB along AE+projection of AD along AE)=AE (projection of AC along AE), which is the work done by the resultant force.

From the above reasoning we can therefore state that to calculate the work done by any number of forces we may replace any two forces by their resultant and then combine this resultant with the third force, and so on, so that finally the total work done by any number of forces will be equal to the work done by their resultant. We can also state that if the whole system of forces is in equilibrium, then the total work done will be zero.

GRAPHICAL REPRESENTATION OF WORK

In Fig. 27 (*a*) F represents to scale a constant force, and S represents the displacement.

Work done=force×distance=FS, which is the area of the rectangle.

In Fig. 27 (*b*) the force F varies whilst acting through a distance S. We can employ the mid-ordinate rule to find the average force F_1, and this force multiplied by the distance S will represent the work done, which product will also give the area of the irregular figure.

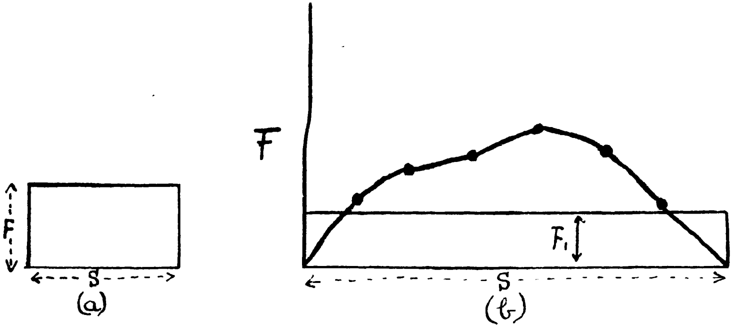


FIG. 27.

In the case just considered F_1 represents the average force, and this average force multiplied by the displacement gives the work done, which is also the work done by a variable force.

In finding a uniform force which will do the same amount of work as a variable force when moving through a definite distance, we are said to obtain the mean effort, and referring to Fig. 27, we can state that the mean effort

$$=\frac{\text{area below force curve}}{\text{displacement}}.$$

WORK DONE DURING ROTATION

Fig. 28 shows a force of P lbs. acting tangentially to a circle of radius R ft. In one complete revolution the force will act through a distance $2\pi R$ ft., and therefore at N revs. per min. total work done$=P\,.\,2\pi RN$ ft.-lbs.

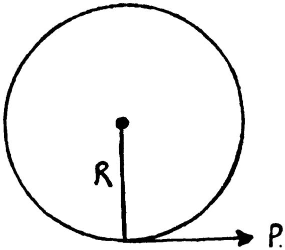


FIG. 28.

NOTE.—If the angle is measured in radians (1 rev.$=2\pi$ radians), then work done = moment of force × angle turned through in radians. (For the definition of moment of a force see Chapter IV.)

Example 2.—What force must be applied at the circumference of a pulley 2 ft. diameter in order to do 26,400 ft.-lbs. of work in 70 revolutions ?

$$\text{Work}=26400 \text{ ft.-lbs.}=\text{force}\times\text{distance}.$$

In 70 revolutions a point on the circumference of the pulley will travel

$$\pi\,.\,2\times 70=\frac{22}{7}\times 2\times 70=440 \text{ ft.}$$

$$\text{Therefore}\quad \text{force}=\frac{\text{work done}}{\text{displacement}}=\frac{26400 \text{ ft.-lbs.}}{440 \text{ ft.}}=60 \text{ lbs.}$$

ENERGY AND POWER

If a body can do work, it is said to possess energy, which may be expressed in one or more of several forms. For example, the energy possessed by a body may be potential (due to position) or kinetic (due to motion), and these two forms of energy will be our chief consideration in this work. Other forms of energy are associated with chemical action, electricity, heat, light, and sound.

Long experiment over many years has established a principle known as the Conservation of Energy, which states that it is impossible to create energy or to destroy it, but it may be transformed from any one form to a different form. A machine will not perform any work until work has been done on the machine, and the work it gives out for useful purposes is always less than the work put in.

The difference between the work put in a machine and the useful work given out is due to energy transformation, *i.e.*, some of the work put in is required to overcome frictional resistances and may manifest itself in the form of heat. In the design of any machine the engineer tries to keep the difference between the work put in and the work given out as small as possible.

If you lift a 10-lb. weight through 5 ft. you will perform 50 ft.-lbs. of work, and the weight will then possess 50 ft.-lbs. of potential energy. This energy will be given out when the weight is allowed to fall to the ground, and during its fall the potential energy is transformed into kinetic energy, the potential energy at the beginning of its fall being equal to the kinetic energy at the end of the fall.

The kinetic energy possessed by a body depends on the mass of the body and on the square of its speed. If M=mass of a body in pounds and V=its speed in feet per second, then the kinetic energy$=\frac{1}{2}MV^2$ foot-poundals, or $\frac{1}{2}\frac{MV^2}{g}$ ft.-lbs.

Example 3.—An iron ball weighing 5 lbs. is shot vertically upwards and rises to a height of 36 ft. Calculate the kinetic energy it possessed at the commencement of its motion.

Potential energy at the highest point=kinetic energy at the beginning of its motion$=5\times36=180$ ft.-lbs.

Without making use of the Conservation of Energy we can find the kinetic energy it possessed at the beginning of its motion by finding the velocity of projection.

If V=velocity of projection and S=height to which the ball rises, then $V^2=2gS$, *i.e.*,

$$V^2=2\times32\times36, \text{ or } V=\sqrt{64\times36}=48 \text{ ft. per sec.}$$

$$\text{Kinetic energy}=\frac{1}{2}\frac{MV^2}{g}=\frac{1}{2}\times\frac{5\times48\times48}{32}=180 \text{ ft.-lbs.}$$

EXPERIMENT 5. *To Determine the Energy Stored in a Flywheel.*—An arrangement, such as that shown in Fig. 29, may be used for this experiment.

A weight W is attached to a rope which is wound round the axle and is just long enough to free itself from the axle when the weight touches the ground. The wheel is turned round by hand until the weight W is at a height H ft. above the ground. The weight is released, and the time taken to fall to the ground is noted by means of a stop-watch. The experiment is then repeated, and the total revolutions noted for the wheel to come to rest.

Let $E=$energy in the wheel, *i.e.*, $E+$kinetic energy of the weight when falling$=$potential energy of weight when at its height H ft. above the ground. We therefore have energy in the wheel $E=WH-\frac{WV^2}{2g}$ where V is the maximum velocity

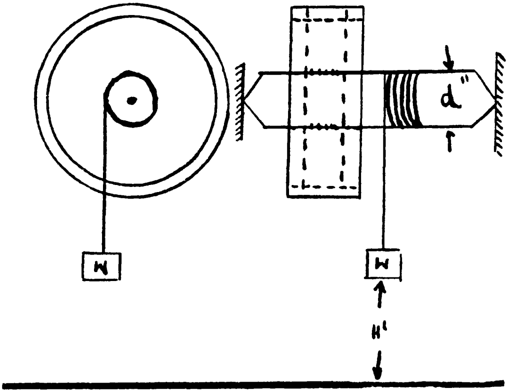


Fig. 29.

of the weight in feet per second. If T secs.$=$time for the weight to reach the ground, the student should prove that $H=\frac{V}{2}T$, *i.e.*, $V=\frac{2H}{T}$, or $V^2=\frac{4H^2}{T^2}$. Therefore, substituting this value for V^2 in our formula for the energy in the wheel, we have

$$E=WH-\frac{4WH^2}{2gT^2}.$$

Now this energy is given out by the wheel in coming to rest, *i.e.*, it is used to overcome friction at the bearings. If the wheel makes N revolutions before coming to rest, then the energy used per revolution$=\frac{E}{N}$, and if n=revolutions required for the weight to reach the ground, then energy used to overcome friction during the fall of the weight$=\frac{E}{N}\cdot n=E_1$. Therefore we have total energy in the wheel$=(E-E_1)$ ft.-lbs.

Calculate this quantity from the following experimental particulars :—

Axle Diameter.	Weight.	Height through which Weight Falls.	Time for Weight to Reach Ground.	Revolutions whilst Weight Falls.
$d=1{\cdot}5$ in.	$W=7$ lbs.	$H=5$ ft.	$T=13{\cdot}5$ secs.	$n=\frac{H}{\pi d}$.

Total revolutions required for wheel to come to rest $N=52{\cdot}5$.

We have already seen that when a force F acts on a mass M and causes an acceleration a, then $F=Ma$. We have also seen that if the velocity of a body changes from u to V whilst moving through a distance S, then $V^2-u^2=2aS$. If, then, we multiply both sides of this equation by $\frac{1}{2}M$, we have

$$\tfrac{1}{2}MV^2-\tfrac{1}{2}MU^2=\frac{2}{2}MaS=MaS=\text{force}\times\text{distance}=\text{work done}.$$

In other words, whenever a force does work, the amount of work done will be represented by the increase in kinetic energy.

Power is defined as the rate of doing work, *i.e.*, if the rate of working is steady it is the ratio $\frac{\text{work done}}{\text{time taken}}$, the engineer's unit being called the horse-power, which is work done at the rate of 33,000 ft.-lbs. per min., or 550 ft.-lbs. per sec. In electrical engineering the unit of power is called the watt, which is equal to 10^7 (ten million) ergs per sec. Now, 1 ft.$=30{\cdot}48$ cm., 1 lb.$=454$ grm., and $g=980$ cm./sec.^{2}, therefore 1 ft.-lb.$=30{\cdot}48\times454\times980=1{\cdot}356\times10^7$ ergs, so that 1 H.P., *i.e.*, 550 ft.-lbs. per sec.$=550\times1{\cdot}356\times10^7$ ergs per sec.$=746$ watts, a result which should be remembered.

Example 4.—Calculate the horse-power of an engine which draws a train at a speed of 45 m.p.h. against a total resistance of 1,000 lbs.

45 m.p.h.=66 ft. per sec., so that the work done per second against the resistance=1,000×66 ft.-lbs., and since 1 H.P.=550 ft.-lbs. per sec.,

$$\text{Horse-power required}=\frac{1000\times 66}{550}=120.$$

Example 5.—What is the total load in tons that a traction engine of 25 H.P. is capable of drawing at the rate of 6 miles an hour against a resistance of 20 lbs. per ton ?

Let W=load in tons, then resistance=20 W lbs.

$$\text{Work done per second}=25\times 550 \text{ ft.-lbs. per sec.}$$

$$\text{Work done per second against resistance}=20W\times 8{\cdot}8 \text{ ft.-lbs.}$$

Therefore $$20W\times 8{\cdot}8=25\times 550,$$

or $$W=\frac{25\times 550}{20\times 8{\cdot}8}=78\tfrac{1}{8} \text{ tons.}$$

Example 6.—Determine the power in watts required to lift 15 tons through 10 ft. in 20 mins.

$$\textit{Work in foot-pounds per minute}=\frac{15\times 2240\times 10}{20}=16800.$$

Therefore $$\text{horse-power required}=\frac{16800}{33000}=0{\cdot}509,$$

i.e., power required in watts=0·509×746=379·714.

ENERGY TRANSMISSION

In an engineering workshop we generally find that energy may be transmitted from one point to another by means of pulleys mounted on shafts, the pulleys being connected either by leather belts, cotton or steel ropes, or by chains. In this work we are not concerned with the advantages and disadvantages possessed by each of these drives, but the student should be able to state them for himself when he has had experience with the various types.

In Fig. 30 A and B represent two pulleys mounted on parallel shafts and connected by a belt, A driving B in a clockwise direction by means of the open belt, or in an anticlockwise direction by means of the crossed belt shown dotted.

Suppose D is the diameter of pulley A and *d* that of B.

When A rotates once, a point on its circumference will travel a distance πD, and assuming that the belt does not slip on either pulley, a point on the circumference of B will move through an equal distance, which is given by $\frac{\pi D}{\pi d}$ or $\frac{D}{d}$. From this we can see that if N_A=revolutions per minute of A, and N_B=revolutions per minute of B, then $\frac{N_B}{N_A}=\frac{D}{d}$, or in words we can state that the speeds of two shafts are inversely proportional to the diameters of the pulleys mounted on them.

NOTE.—The above reasoning applies to both open and crossed belts, and the student should examine, sketch, and describe the mechanism by means of which the open and crossed belts are changed on the pulley on the driven shaft.

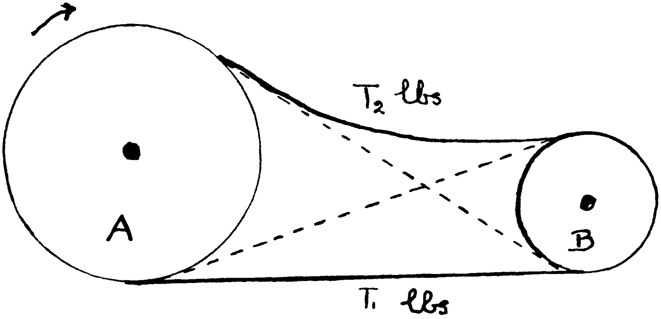


FIG. 30.

Example 7.—A pulley 4 in. in diameter is fixed to the spindle of a fan which is required to rotate at 1,600 revs. per min. If the driving shaft rotates at 400 revs. per min., what is the diameter of the pulley on this shaft which will give the required speed ?

$$\frac{\text{Speed of driving pulley}}{\text{Speed of driven pulley}}=\frac{\text{diameter of driven pulley}}{\text{diameter of driving pulley}},$$

i.e., $$\frac{400}{1600}=\frac{4 \text{ in.}}{\text{required diameter}},$$

or $$\text{required diameter}=\frac{1600\times 4}{400}=16 \text{ in.}$$

Exercise.—Prove that the revolutions per unit time of two wheels in gear are inversely proportional to the numbers of teeth on the wheels.

Example 8.—A driving pulley A, 24 in. diameter, rotates at 120 revs. per min., and it drives a pulley B, 20 in. diameter, by means of a belt. On the same shaft as pulley B there is a pulley C, 12 in. diameter, which drives a pulley D, also 12 in. diameter. On the same shaft as pulley D there is a wheel of 50 teeth which drives a wheel F containing 40 teeth. Determine the revolutions per minute of the wheel F.

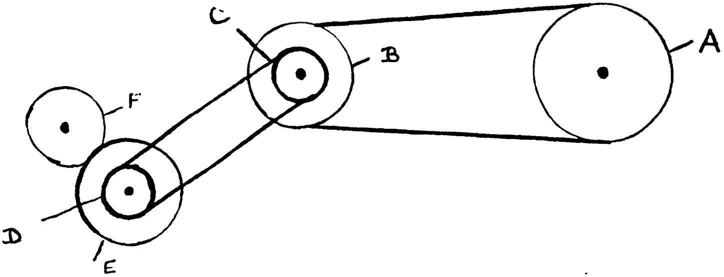


FIG. 31.

The arrangement is shown in Fig. 31. We have

$$\frac{120}{\text{speed of B}}=\frac{20}{24},$$

i.e., $$\text{speed of B}=\frac{24\times 120}{20}=144 \text{ revs. per min.}$$

Since B and C are on the same shaft, the speed of C will also be 144 revs. per min., which, as you will see, is the speed of D and E.

Therefore $$\frac{144}{\text{speed of F}}=\frac{40}{50},$$

i.e., $$\text{speed of F}=\frac{144\times 50}{40}=180 \text{ revs. per min.}$$

The student will have noticed that when one pulley drives another by means of a belt one part of the belt is tight and the other part which sags is slack. For example, in Fig. 30, if A is the driving pulley and it rotates in the direction of the *arrow, the tight and slack parts of the belt will be as shown.* Suppose T_1 lbs. is the pull in the tight side, and T_2 lbs. is the pull on the slack side, then the difference (T_1-T_2) lbs. we can regard as the driving force. If the belt is moving at a speed of, say, V ft. per min., then the work done per minute by the belt will be $(T_1-T_2)V$ ft.-lbs., and therefore the horse-power developed $=\frac{(T_1-T_2)V}{33000}$.

In practice it is much more convenient to measure the diameter of the driving pulley and to note its speed in revolutions per minute rather than to determine directly the speed of the belt in feet per minute. If D=diameter of the driving pulley in feet and N=revolutions per minute, then V in the above formula is given by the product πDN, so that we have

$$\text{Horse-power}=\frac{(T_1-T_2)\pi DN}{33000},$$

from which we can find any one quantity if the others are known.

Effects of Centrifugal Force in a Belt Drive

From the above reasoning it would appear that as we increase the speed of rotation of the driving pulley we increase the horse-power developed, but this is only the case up to a certain point. Beyond this point the effects of centrifugal force have to be taken into account. At high speeds, owing to centrifugal force, the belt tends to leave the pulley, and this causes excessive slip and consequent loss of power. Extra tension will be called into play on the tight and slack sides of the belt, and this tension will be in addition to that required for driving purposes. If the speed becomes too great, the belt may not be able to withstand the extra tension and it will, of course, collapse. Fig. 32 shows the type of curve we get when horse-power is plotted against the speed of the belt.

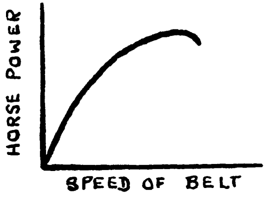


Fig. 32.

Example 9.—The tension on the tight side of a belt is twice that on the slack side. Calculate what width of belt running at a speed of 1,500 ft. per min. will be required in order to transmit 10 H.P., assuming that a belt 1 in. wide can safely withstand a force of 100 lbs.

If T_1=tension on the tight side of the belt and T_2=tension on the slack side, then

$$\frac{T_1}{T_2}=\frac{2}{1}, \textit{ i.e.}, T_1=2T_2.$$

Therefore in our formula for horse-power transmitted we have

$$10=\frac{(2T_2-T_2)1500}{33000}, \textit{ i.e.}, 15T_2=3300,$$

whence $T_2=220$ lbs.

The tension on the tight side of the belt will therefore be 440 lbs., and the required width of belt will be $\frac{440}{100}=4 \cdot 4$ in.

ENERGY TRANSMITTED BY TOOTHED WHEELS IN GEAR

In Fig. 33 (not drawn to scale) is shown one form of toothed gearing in which A is the driver and B the driven wheel. In the diagram three circles are shown on each wheel, the smallest circle in each case being known as the root circle, and the largest circle being known as the addendum circle. The middle circle, which is not exactly half-way between the other two, is called the pitch circle, and the pitch of the teeth is defined as the distance from the centre of one tooth to the centre of the next measured along the pitch circle.

The student should examine and sketch toothed wheels, and should note the general proportions. Roughly, the height of the tooth H (Fig. 33) is about 0·7 times the pitch. The thickness T is just under half the pitch, and the space S just over half the pitch. The width of the tooth will, of course, depend on the nature of the work it has to perform.

In Fig. 33 the two shafts on which the toothed wheels are fixed are parallel, and the wheels are an example of what is called spur gearing. In the course of his work the student will have opportunity for examining other forms of gearing, such as the rack and pinion, worm and wheel, bevel and spiral gears. He should sketch and describe the various types, explaining why they are used in any particular machine.

Again referring to Fig. 33, if a force P lbs. acts tangentially to the circumference of the driving wheel A, then the work done by P in 1 rev. will be $P\pi D$ where D is the diameter of the wheel. Assuming no loss of energy due to friction, the work obtained from the driven wheel B will be equal to the work put in the driver A, so that if A rotates at N revs. per min., work done per minute$=P\pi DN$, and therefore horse-power developed$=\frac{P\pi DN}{33000}$, from which we can find any one quantity if the others are known.

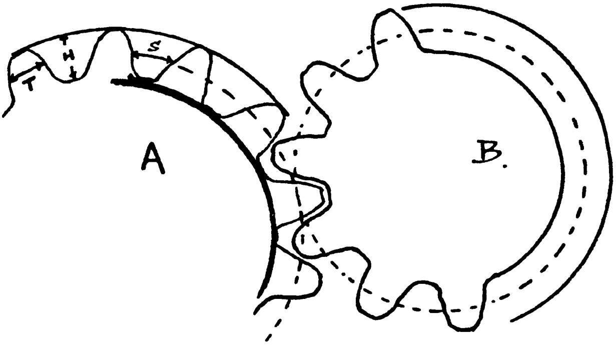


FIG. 33.

Example 10.—A train of wheels transmits 5 H.P. The driving wheel has 60 teeth, and the pitch is 1 in. How many revolutions per minute will it make if the pressure on the teeth is 140 lbs. ?

The circumference=pitch × number of teeth$=\frac{60}{12}=5$ ft.

Therefore $$5=\frac{140\times5\times N}{33000},$$

whence $$N=235\cdot7 \text{ revs. per min.}$$

THIRD SET OF EXAMPLES

1. Define the terms force, work, kinetic energy, potential energy, and horse-power, explaining the units in which each may be measured.

Calculate the horse-power of a steam pump which raises 10 tons of water 10 ft. high every minute.

2. Define foot-poundal and foot-pound.

Explain why the work done per mile on a train by the engine is greater when the train is being accelerated than when it is travelling uniformly, the frictional resistance to the motion being assumed to be the same in each case. L.M.

3. Define the work done by a force.

A force of 80 poundals acts vertically upwards on a mass of 1 lb., which is initially at rest. How much work will be done by the force in 3 secs., and what will then be the kinetic energy of the mass if the only other force acting on it is its weight? L.M.

4. A bullet of mass $\frac{1}{2}$ oz. moving with a velocity of 1,000 ft. per sec. penetrates a fixed wooden board and emerges with a velocity of 200 ft. per sec. Calculate the work done by the bullet in piercing the board. If the board is 4 in. thick, find the average force exerted by the bullet. L.M.

5. What do you understand by the principle of the Conservation of Energy?

Describe the changes in the energy of the bob of a simple pendulum when swinging freely. Why does such a pendulum gradually come to rest? N.M.

6. A chain is 80 ft. long and it weighs 10 lbs. per ft. Calculate the work done in winding the chain on to a drum.

7. Prove that 1 H.P. is equivalent to 746 watts.

8. Determine the power in watts which will be required in order to lift a weight of 10 tons through 5 ft. in 2 mins.

9. Determine the load in tons that an engine of 30 H.P. can draw along the level at a speed of 6 miles an hour, the resistance to be overcome being 25 lbs. per ton.

10. An engine driving pulley is 18 in. diameter and runs at 160 revs. per min. Calculate the speed of the belt in feet

per minute, neglecting slip. What horse-power is transmitted if the effective driving tension is 50 lbs.? U.L.C.I.

11. A line of shafting running at 200 revs. per min. drives a countershaft by means of a belt running on a pulley 30 in. diameter. The belt is 3 in. wide, and the ratio of the tensions on the tight and slack sides is 5 : 2, and the safe pull per inch of width is 80 lbs. What horse-power may this belt be expected to transmit at the given speed? U.L.C.I.

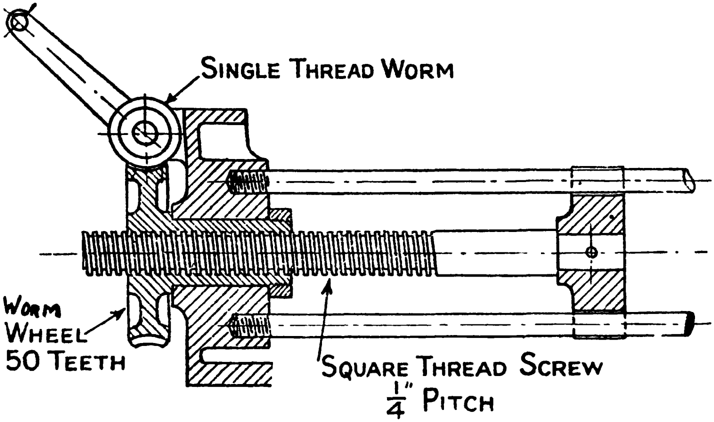


FIG. 34.

12. Express in horse-power the rate of doing work in each of the following cases :—

(*a*) A horse drawing a load of $1\frac{1}{2}$ tons on the level at the rate of 3 miles an hour, the resistance being 60 lbs. per ton.

(*b*) Five tons of coal raised vertically at the rate of 55 ft. per sec.

(*c*) A belt exerting an effective pull of 200 lbs. tangentially to the rim of a pulley 3 ft. in diameter when the pulley is rotating at 140 revs. per min.

U.L.C.I.

13. A worm-wheel with 50 teeth is mounted and forms the nut of a screw $\frac{1}{4}$ in. pitch. Guides prevent the screw from turning, and the worm-wheel is driven by a single-thread worm (see Fig. 34).

Calculate :

(1) The angular movement of the worm necessary to cause one-thousandth of an inch axial travel of the screw.

(2) The travel of the screw that would result from $3\frac{1}{2}$ revs. of the worm. U.L.C.I.

14. In designing the layout of the machines in a new workshop, you have the choice of fixing the main line-shaft (*a*) overhead, (*b*) on bearing pedestals at the back of the machines, (*c*) in a covered trench with belts coming up through slits in the covering boards to the countershafts. Discuss the relative advantages and disadvantages of each arrangement.
U.L.C.I.

CHAPTER IV

ACTION OF FORCES ON BODIES AT REST. GRAPHIC STATICS

In this chapter we shall consider one or two cases in which forces act on a body and the body remains at rest, Statics being the name given to this particular section of our work.

A force, which was defined in Chapter II., may be represented by a finite straight line when the length of the line is made equal to the magnitude of the force to some convenient scale. The direction of the line represents the direction of the force, an arrowhead shows the " sense " of the force, and the end of the line sometimes, but not always, shows the point of application of the force.

For example, one method of naming a force is by letters placed at the ends of the line such as $_a/$ when it is understood that the sense of the force is from the first-named letter to the second. Another method, which is known as Bow's Notation, is to place letters on either side of the line, like A↑B. You will find this method of representing a force very convenient in dealing with the solution of problems graphically.

In Chapter II. the weight of a body was defined as that force with which it is attracted towards the centre of the earth. If an elongated body is uniform throughout its length, we can assume that its weight acts at its centre, and this point, which is the point about which the body will balance, we define as the centre of gravity of the body.

Note.—At this stage of our work it is very important that the student should remember that in all cases in which the weight of a body is taken into account the weight acts at the centre of gravity of the body, and, further, that if the body is uniform and has a simple geometrical form its centre of gravity is the geometrical centre of the body. If the body is not uniform, the centre of gravity will be stated, and later on you will be able to find its position.

EXPERIMENT 6. *To find the Centre of Gravity of a Thin Sheet of Metal.*—Fig. 35 shows the method of doing this experiment in the case of a square sheet of tin ABCD, and the method is just the same for other shapes.

Bore a number of holes in the piece of metal and suspend it on a smooth pin, which also carries a piece of thread at the end of which is attached a small weight W. Allow the system to come to rest and mark the direction of the thread, *i.e.*, AC. Repeat for different positions and note the point where the various lines intersect, say G, which is the centre of gravity of the body.

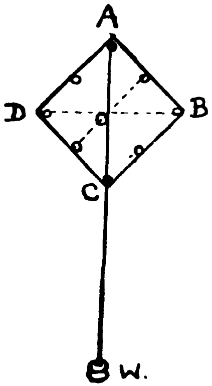


FIG. 35.

Perform the experiment for bodies of different shapes, tabulate your results, and remember the results in the case of the regular figures.

NOTE.—In this experiment we have neglected the thickness of the body so that G may be defined as the centre of area.

PARALLEL FORCES

EXPERIMENT 7. *To find the Conditions under which a Number of Parallel Forces acting on a Body keep it in Equilibrium.*—First of all obtain a beam about 30 in. long and support it at each end by spring balances A and B, as shown in Fig. 36. Note the spring-balance readings and call this the zero reading.

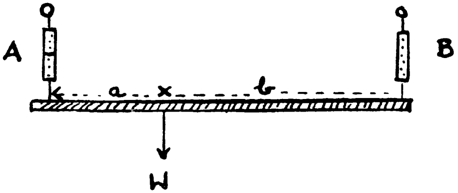


FIG. 36.

Place a weight W lbs. at different positions along its length, note the spring-balance readings, and in each case subtract the zero reading.

Tabulate your results and state conclusions.

Now repeat the experiment with two or more weights placed in different positions on the beam (Fig. 37), again tabulating your results and stating your conclusions.

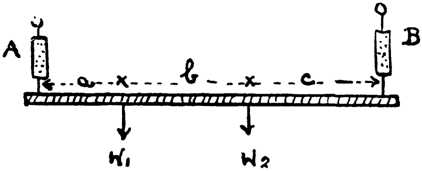


FIG. 37.

In these experiments the weights on the beam and the weight of the beam itself are pulling downwards and the spring balances are pulling upwards, and if you have performed the experiments carefully you will be able to state the first rule of equilibrium, which is that when a body is at rest under the action of a number of parallel forces the sum of the forces acting in one direction is equal to the sum of the forces acting in the opposite direction.

To establish the second rule of equilibrium take the same beam which you used in order to find the first rule and support it at its centre of gravity (Fig. 38). (In a uniform beam remember that the centre of gravity is its centre of length.)

When so supported the beam remains in a horizontal position. Place a weight W_1 at a distance *a* in. from the centre of the beam, and the beam immediately turns round its point of support in an anti-clockwise direction. This tendency of a force to turn a body about its point of support we call the moment of the force, or turning moment, or torque, and it is measured by the product force × perpendicular distance of the force from the point of support. If the weight is in pounds and the distance measured in feet, then the unit of torque or turning moment is the pound-foot.

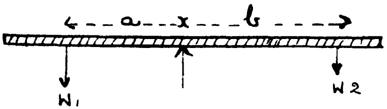


FIG. 38.

NOTE.—Do not confuse the pound-foot with the foot-pound which, as you know, is the unit of work.

In order to restore the beam into a horizontal position a weight W_2 must be placed at a distance b from the point of support. Do this, and when the beam is horizontal prove that $W_1a=W_2b$.

Repeat the experiment for different weights and different positions, then arrange the experiment, as shown in Fig. 39, and prove that when the beam is horizontal

$$W_1b+W_2a=W_3c+W_4d+W_5e.$$

The experiment gives us our second rule of equilibrium, which states that when a body is in equilibrium under the action of a number of parallel forces the sum of the moments of the forces tending to turn the body about any point in a clockwise direction is equal to the sum of the moments of the forces tending to turn the body in an anti-clockwise direction about the same point.

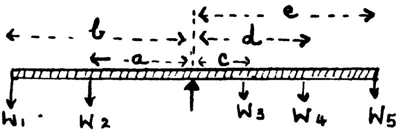


FIG. 39.

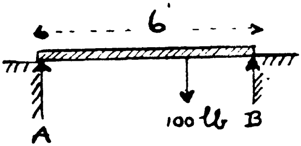


FIG. 40.

Exercise.—Find the weight of the beam you have used in Experiment 7 without using a spring balance.

Example 1.—A plank is used to bridge a trench 6 ft. wide. Neglecting the weight of the plank, find the pressure on the supports when a load of 100 lbs. is placed on the plank at a distance of 1 ft. from the centre.

Let A and B represent the reactions of the supports (Fig. 40), then, since 100 lbs. is the total force acting downwards, A+B must equal 100 lbs.

To find the reaction A take moments round the end B. The reaction A tends to turn the plank round B in a clockwise direction, and the 100-lb. weight tends to turn the plank round the same point in an anti-clockwise direction.

To find the reaction A we have taking moments

$$6A=100\times 2=200.$$

Therefore $$A=33\tfrac{1}{3} \text{ lbs.}$$

Therefore, since $A+B=100$ lbs., we have

$$B=100-A=100-33\tfrac{1}{3}=66\tfrac{2}{3} \text{ lbs.}$$

(To find the reaction B by taking moments round A we have $6B=100\times 4=400$, whence $B=66\tfrac{2}{3}$ lbs. as before.)

Example 2.—The horizontal roadway of a bridge weighing 5 tons is 30 ft. long, and it rests on supports at each end. Calculate the thrust on each support when a lorry weighing 1 ton is (1) half-way across and (2) when it is two-thirds the way across.

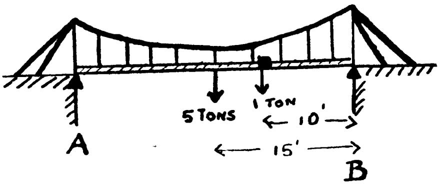


FIG. 41.

(1) When the lorry is half-way across, the total weight acting downwards at the centre of the bridge is 6 tons. The supports react in an upward direction, so that each support must take half the weight, viz., 3 tons.

(2) Let A and B represent the reactions of the supports (Fig. 41). Taking moments round B to find A, we have

$$30A=(5\times 15)+(1\times 10)=75+10=85,$$

whence $A=2\tfrac{5}{6}$ tons.

Since $A+B=6$ tons, $B=6-A=6-2\tfrac{5}{6}=3\tfrac{1}{6}$ tons.

As an exercise find B by taking moments round A.

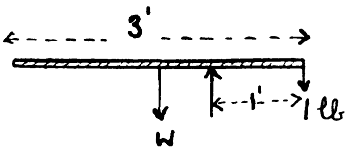


FIG. 42.

Example 3.—A rod 3 ft. long balances about a point 1 ft. from one end when a load of 1 lb. is suspended at that end. Calculate the weight of the rod.

Let W=weight of the rod which acts at its centre (Fig. 42). Taking moments round the point of support, we have

$$W\times\tfrac{1}{2}=1\times 1, \textit{ i.e.}, \tfrac{1}{2}W=1,$$

whence $W=2$ lbs.

Forces acting in the same direction are spoken of as *like* parallel forces, those acting in opposite directions are known as *unlike* parallel forces, and if we denote the downward direction as positive, then the upward direction must be considered negative. Our rules of equilibrium for parallel forces, as obtained in Experiment 7, can therefore be stated in algebraic language as follows :—

A body is in equilibrium under the action of a number of parallel forces when (1) the algebraic sum of the forces is zero, and (2) when the algebraic sum of the moments of all the forces acting about any point is zero.

Suppose we have two *equal* forces F acting on a bar AB pivoted at C, as shown in Fig. 43. The algebraic sum of these forces is F—F=0, but the rod will not remain in equilibrium. Such a system of parallel forces constitutes a couple, and taking moments round the point C we have, since each force is tending to turn the rod in an anti-clockwise direction, F . AC+F . BC, or F(AC+BC), or F . AB, *i.e.*, the moment of a couple is either force multiplied by the perpendicular distance between the lines of action of the forces. It is easy to see that a single force cannot act on the rod against the couple and keep it in equilibrium. In order to keep the rod in equilibrium another couple must be applied in the same plane, having the same moment but acting in the opposite direction.

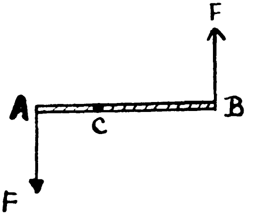


FIG. 43.

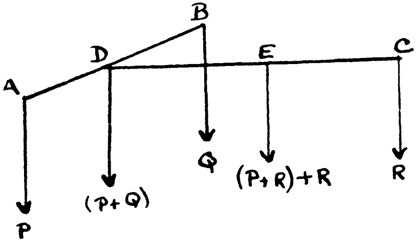


FIG. 44.

THEORY OF PARALLEL FORCES

Suppose that we have a system of parallel forces PQR . . . acting at the points ABC . . ., as shown in Fig. 44. The two forces P and Q will be equivalent to a single parallel force

(P+Q) acting through a certain point D in AB, which is found by the relation P . AD=Q . DB. Also, the forces (P+Q) acting at D and R acting at C will be equivalent to a single parallel force (P+Q)+R acting at a certain point E in DC given by the relation (P+Q)DE=R . EC. Proceeding as above, we can state that the whole system of parallel forces is equivalent to a single force equal in magnitude to the sum of the separate forces and acting through a certain point G, the position of which depends only on the ratio of the forces PQR, etc. This point depends neither on the absolute magnitudes nor directions of the separate forces, and would not be altered even if the forces were turned through an angle about their respective points of application, provided, of course, that their directions remained parallel, and it is defined as the centre of gravity of the system of parallel forces.

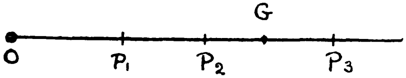


FIG. 45.

To find the centre of gravity of a system of parallel forces in one straight line.

Let $M_1M_2M_3$ . . . represent the masses of the particles at distances $X_1X_2X_3$ . . . (positive or negative) from a fixed point O on the straight line. Let G be the centre of gravity and $\bar{X}$ be the distance of G from the point O. Now suppose we have a number of forces proportional to $M_1M_2M_3$ . . . and acting at points $P_1P_2P_3$ . . . and in a direction at right angles to the line (Fig. 45), the resultant force* being $M_1+M_2+M_3+$. . . .

Taking moments of these forces about the point O, we have

$$M_1X_1+M_2X_2+M_3X_3+\ \dots\ =(M_1+M_2+M_3+\ \dots)\bar{X},$$

whence

$$\bar{X}=\frac{M_1X_1+M_2X_2+M_3X_3+\ \dots}{M_1+M_2+M_3+\ \dots}.$$

---

* The resultant force is defined as the single force which is statically equivalent to any number of forces. A force equal in magnitude to the resultant but acting in the opposite direction is known as the equilibrant.

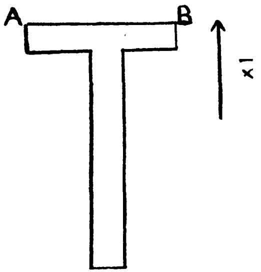


Fig. 46.

Note. — In this work, under certain conditions, centre of area or centre of mass may be used for centre of gravity.

Example 4.—Find the position of the centre of area of the T section shown in Fig. 46, flange $=4$ in. $\times\frac{1}{2}$ in., web $=6$ in. $\times\frac{1}{2}$ in.

Let $\bar{X}$ be the distance of the centre of area from the edge AB. Area of the two rectangles $=2+3=5$ sq. in.

Therefore, taking moments round the edge AB, we have

$$5\bar{X}=(2\times0{\cdot}25)+(3\times3{\cdot}5)=0{\cdot}5+10{\cdot}5=11.$$

Therefore $$\bar{X}=2{\cdot}2 \text{ in.}$$

Non-parallel Forces

Experiment 8.—Arrange three pieces of string, a weight, and two ordinary spring balances in a vertical plane, as shown in Fig. 47. Allow the system to come to rest and then proceed to draw AB parallel to the string R and representing to scale the given weight W. From B draw BC parallel to the string P, and from A draw AC parallel to the string Q. Note the spring-balance readings and compare these readings with the lengths of BC and AC. You will find that AC and BC represent the spring-balance readings to the same scale that AB represents the suspended weight.

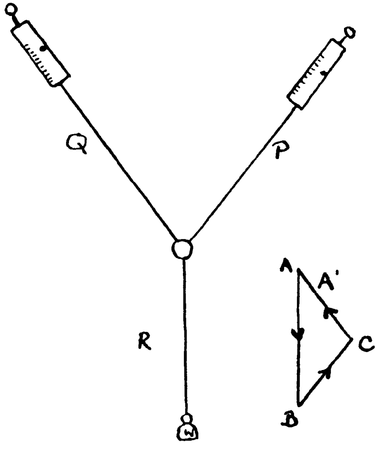


Fig. 47.

From this experiment we may state that if three forces acting on a particle are in equilibrium, and any triangle be constructed having its sides parallel to the respective forces, then the forces will be to one another in the same ratio as the sides of the triangle. In Fig. 47 ABC is such a triangle, having AB parallel to R, BC parallel to P, and AC parallel to Q. Also, since AB represents the weight W, then CA must represent the spring-balance reading Q on the same scale. If this is not the case let CA′ represent Q, and then the resultant of P and Q will be represented by BA′, and therefore cannot be in equilibrium with R, which is parallel to AB. Therefore A′ must coincide with A, and we have

$$\frac{BC}{CA}=\frac{P}{Q}.$$

This result is known as the Triangle of Forces, which states that if a body is acted on by three forces which are in equilibrium, then the magnitudes of the forces will be proportional to the sides of a triangle drawn parallel to the direction of the respective forces, and if arrowheads are placed on the sides of the triangle to show the sense of the forces, the arrowheads will follow one another round the triangle.

From this it follows that if we are given the directions of three forces which are in equilibrium, and the magnitude of one of them, we can find the magnitude of the other two.

Example 5.—A coal wagon runs down an inclined plane which is inclined at an angle of 20° to the horizontal. If the wagon when loaded weighs 10 tons, find what force acting in a direction parallel to the incline will keep the wagon at rest.

This problem is represented in Fig. 48. The truck is kept at rest by three forces, viz., its weight, 10 tons, acting vertically downwards, the reaction of the plane which is always perpendicular to the surface, the third force being the pull in the rope P, acting parallel to the incline.

Taking a scale in which 1 in. represents 10 tons, draw *ab* vertically to represent the weight. From *a* draw *ac* parallel to the reaction R, and from *b* draw *bc* parallel to the plane, so that *abc* is our triangle of forces. To the same scale that *ab* represents 10 tons, we find by measurement that the required force *bc* is 3·5 tons.

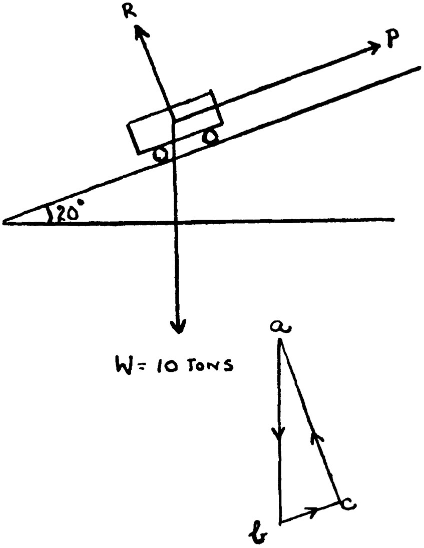

R
P
20°
W = 10 TONS
a
b
c

FIG. 48.

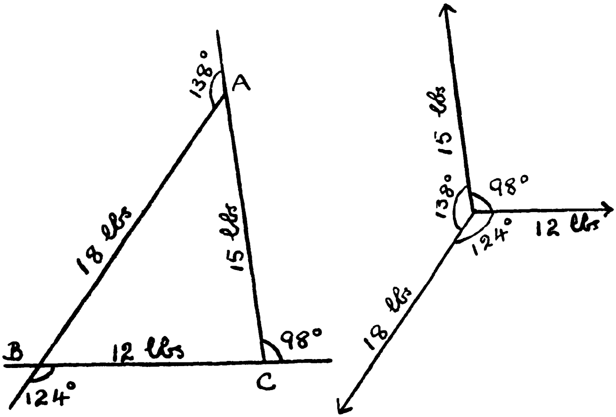

138°
A
18 lbs
15 lbs
B
12 lbs
98°
C
124°
15 lbs
138°
98°
124°
12 lbs
18 lbs

FIG. 49.

Exercise.—Find the force required to keep the above wagon at rest when the force P acts horizontally.

Example 6.—Forces of 12, 15, and 18 lbs. act on a particle and are in equilibrium. Find, graphically, the angles between their lines of action.

The three given forces are in equilibrium, so that we can construct a triangle in which the sides represent the forces. In Fig. 49 ABC is this triangle.

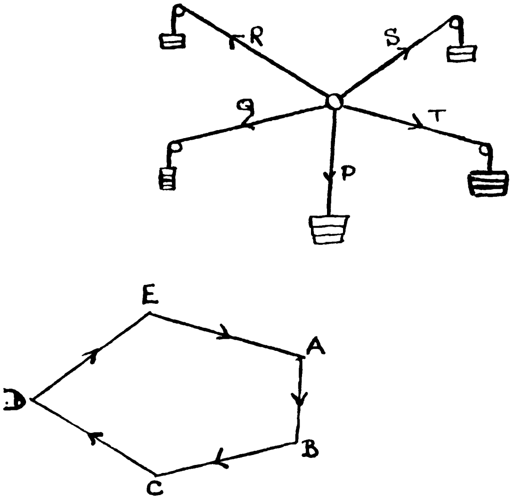


Fig. 50.

The angle between any two of the forces will be the supplement of the corresponding interior angle of the triangle, and by measurement we find the required angles to be as shown.

Experiment 9.—Attach five pieces of string to a small ring, and let each string which passes over a pulley, as shown in Fig. 50, support a weight. Allow the system to come to rest, the forces being P, Q, R, S, and T.

Now draw AB to a convenient scale representing the force P in magnitude and direction. From B draw BC to represent Q, CD to represent R, and DE to represent S.

If the system is in equilibrium, it will be found that EA represents the force T both in magnitude and direction.

From such an experiment we can conclude that if any number of forces act on a particle and no motion takes place, then the magnitudes of the forces will be proportional to the sides of a closed polygon drawn parallel to the direction of the respective forces, and if arrowheads be placed on the sides of this polygon to show the sense of the forces, then the arrowheads will follow one another round the polygon, the result being known as the Polygon of Forces.

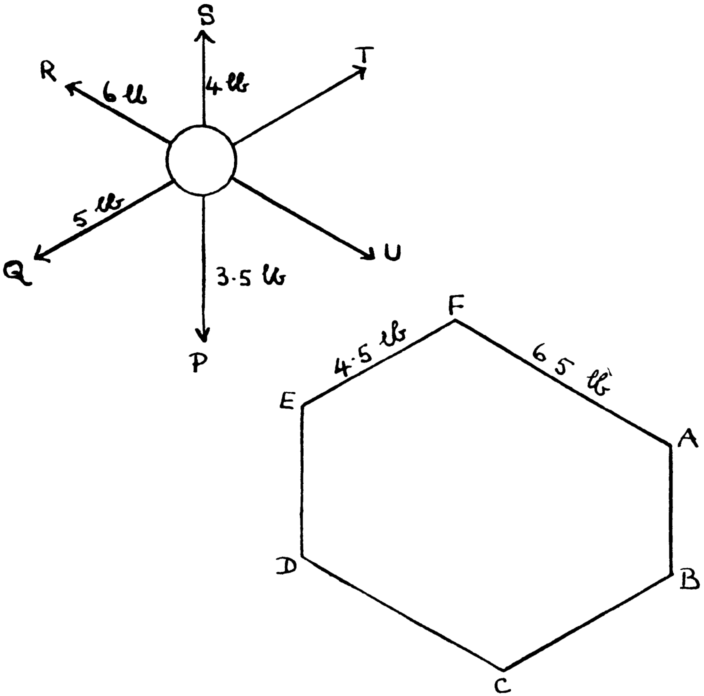


FIG. 51.

Example 7.—Six strings are fixed to a small ring and are equally inclined to one another at an angle of 60°. Four consecutive strings support weights of 3·5, 5, 6, and 4 lbs. respectively. Find what weights will have to be fixed on to the ends of the two remaining strings in order that the ring may be in equilibrium.

Constructing the polygon of forces by the method described, we find that EF and FA, which represent the forces in the two remaining strings, are 4·5 and 6·5 lbs. respectively (see Fig. 51).

ELEMENTS OF GRAPHIC STATICS

The graphical solution of problems is of great value to the engineer, and especially when dealing with what are called Framed Structures. These structures are made up of straight bars pin-jointed at their ends, but the only forces with which we shall deal are tension and compression.

We require two diagrams ; the first, which is lettered according to Bow's notation, shows the actual structure and its loads, and is called the position or structure diagram. The second, which is obtained from the first, is known as the force or vector diagram, and from it we can obtain the forces acting in the actual structure.

The method of obtaining the forces which act in the members of a loaded structure can best be explained by means of a simple example, and once the method is understood it can be applied to more complicated structures.

Example 8.—The horizontal bar of a triangular roof truss is 20 ft. One member is inclined at 60° to the horizontal, and the other is inclined at 30° to the horizontal. Find, graphically, the forces acting in the members of the truss and the reactions of the supports when a load of 100 lbs. is placed at the apex.

The position diagram of the truss and its load is shown at (*a*) (Fig. 52), and this diagram is lettered according to Bow's notation.

In the diagram AB represents the load. The members of the truss are respectively BD, DA, and CD, and the supports are represented by BC and CA.

The force diagram is shown at (*b*) (Fig. 52), and it is obtained as follows :—

Draw *ab* parallel to AB, which represents the load in magnitude and direction, to some convenient scale. Now from *a* draw *ad* parallel to AD, and from *b* draw *bd* parallel to BD. The point of intersection of these two lines fixes *d*. We now draw *dc* parallel to CD, cutting *ab*, which is called the load line, at *c*. To the same scale that *ab* represents 100 lbs., the line *ad* represents the force in AD, *bd* represents that in BD, and *cd* that in CD. Also, *ac* will represent the left-hand reaction, and *cb* the right-hand reaction.

Draw this figure accurately and state your results.

To determine which bars are in tension and which are in compression we must first of all decide upon a definite direction for lettering the structure diagram. In this case the direction is clockwise. Consider the bar DA and either joint connected with that bar. Suppose we fix on the joint connecting the bar DA with the horizontal bar CD. Rotating round this joint in a clockwise direction, we meet the letter A before D. Now place an arrow on the corresponding line in the force diagram pointing from the first-named letter to the second, as shown. Finally, transfer this direction back to the structure diagram and note whether the arrow points towards or from the joint under consideration. In this example the arrow points towards the joint we are considering, and this means

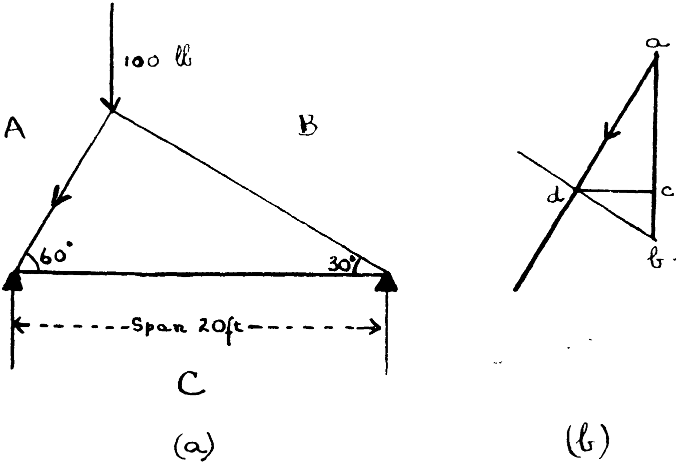


FIG. 52.

that the bar DA is under compression. If the arrow had pointed from the joint, the bar would have been in tension.

Apply this reasoning to the bars BD and CD, and show that BD is in compression and that CD is in tension.

Example 9.—The dimensions of a roof truss are shown at (*a*) (Fig. 53), the load on the apex being 500 lbs.

Draw the force diagram and state which members are in tension and which are in compression.

The force diagram is shown at *b* (Fig. 53). In this case, since the roof truss is symmetrical and the loading is central, each reaction BC and CA will be half the total load of 500 lbs. This fixes *c* half-way between *a* and *b* on the load line. From *a* draw *ad* parallel to AD, and from *c* draw *cd* parallel to CD, the intersection of these two lines fixing *d*. Similarly we fix the point *e*, and then draw *de*, which is, of course, parallel to DE.

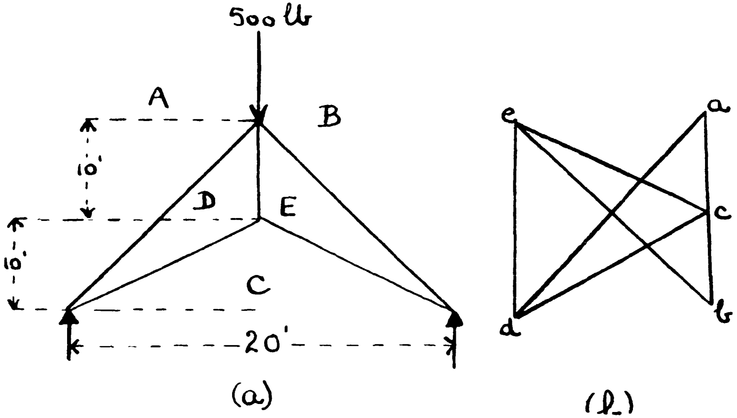


FIG. 53.

Applying the above rule to determine which members are in tension and which are in compression, we find that DE, EC, and CD are in tension, and that BE and DA are in compression.

The student should draw the force diagram to a suitable scale and find the forces which act in the members of the roof truss.

Example 10.—A uniform beam, 20-ft. span, is supported at each end and carries the following loads : $\frac{1}{2}$ ton 5 ft. from the left-hand support, 1 ton at the centre, and 1 ton 5 ft. from the right-hand support. Neglecting the weight of the beam, show that the left-hand reaction is $1\frac{1}{8}$ tons, and that the right-hand reaction is $1\frac{3}{8}$ tons.

We will conclude this chapter with a description of a graphical method of solving the above problem.

The loaded beam is shown at (*a*) (Fig. 54) and it is lettered according to Bow's notation, the right-hand reaction being DE and the left-hand reaction EA. Draw the line of loads, as shown at (*b*) (Fig. 54), and take a point O, which is called a pole, anywhere to the side of *ad*.

Continue the vertical lines, as shown at (*a*), and number the spaces 1, 2, 3, and 4. From O in (*b*) draw lines to *a*, *b*, *c*, and *d*. Returning to (*a*), in space 1 draw a line parallel to O*a*, in space 2 draw a line parallel to O*b*, in space 3 draw a line parallel to O*c*, and in space 4 draw a line parallel to O*d*. Now join the first and last of these lines by the dotted line shown in (*a*), and from O draw a line parallel to this dotted line, and let it cut *ad* at *e*. Measure *de*, the right-hand reaction, and *ea*, the left-hand reaction, and compare the results with those previously obtained.

The closed diagram shown at (*a*) (Fig. 54) is known as the Link or Funicular or Equilibrium Polygon. It is of great importance in graphical work, but at this stage we are not in a position to consider it in greater detail.

FOURTH SET OF EXAMPLES

1. (*a*) A crowbar 5 ft. long rests on a fulcrum 3 in. from one end ; what weight at the end of the bar nearest the fulcrum can be lifted by an effort of 100 lbs. applied at the other end of the crowbar ? If the fulcrum had been at the end of the bar, what weight 3 in. from the fulcrum would 100 lbs. at the other end of the bar move ?

(*b*) Forces of 10 and 35 lbs. weight are to be in balance at the ends of a lever 5 ft. long. How far must the fulcrum be placed from the end at which the 10-lb. weight hangs ?

U.L.C.I.

2. Define the moment of a force about a point.

How would you make experiments illustrating that when

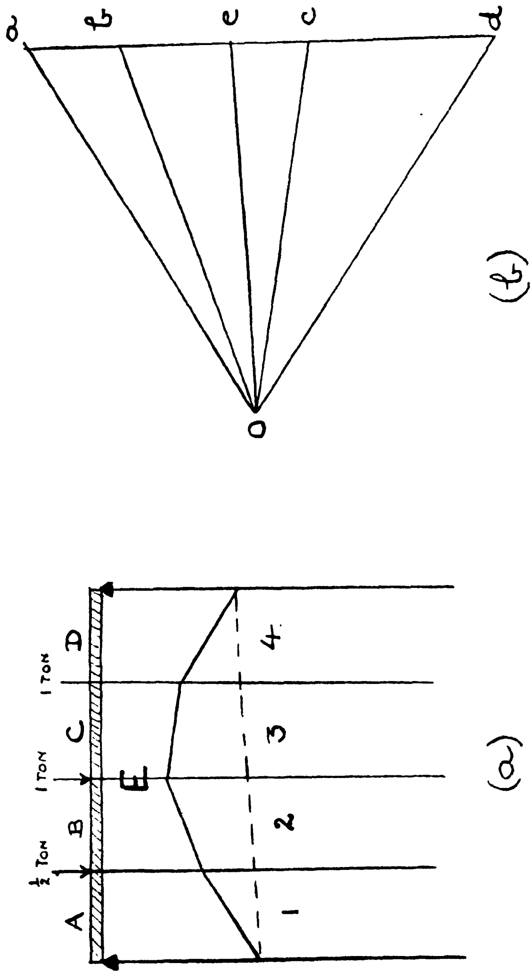


FIG. 54.

a body is in equilibrium under the action of three forces, the sum of the moments about any point is zero? L.M.

3. A uniform pole, weighing 20 lbs. and 6 ft. long, has masses of 10 and 30 lbs. respectively suspended from its ends. Where must the pole be supported to rest horizontal, and what force must be exerted there? L.M.

4. A straight rod ABCD, whose weight may be neglected, rests horizontally over a peg at B and presses upwards against a peg at C. The rod is 5 ft. long, AB is 2 ft., and CD 1 ft. If a load of 10 lbs. is suspended at A and a load of 4 lbs. at D, find the pressures on the pegs. N.M.

5. (*a*) Describe with sketches an experiment designed to establish the laws of equilibrium of parallel forces.

(*b*) A girder 20 ft. long is supported at one end and at a point 5 ft. from the other end. The girder carries a uniformly distributed load (including its own weight) of 5 tons, and a concentrated load of 2 tons at the free end. Find the reactions of the supports. U.L.C.I.

6. A horizontal girder weighing 21 lbs. per foot length rests on supports 20 ft. apart. Vertical loads of 1 and 2 tons are supported by the girder at points 5 and 14 ft. respectively from the left end. Find the reactions of the supports. U.L.C.I.

7. A rod weighing 50 lbs. rests on two supports A and B, one at each end of the rod. If a load of 100 lbs. placed 2 ft. from A causes a pressure of 95 lbs. to be exerted at A, calculate the distance between the supports.

8. (*a*) Explain, with reference to diagrams, the meaning of the terms *resultant*, *equilibrant*, *and component* as applied to forces.

(*b*) A force $P=300$ lbs. is required to have a horizontal component of 180 lbs. Find the angle which the line of action of P must make with the horizontal, and find the vertical component. State the magnitude and direction of the equilibrant of these two components. U.L.C.I.

9. A uniform rod is 3 ft. long and it weighs 1 lb. Find the point about which it will balance when a weight of 6 lbs. is placed on one end and a weight of 8 lbs. is placed 4 in. from the other end.

10. A uniform plank of wood 30 ft. long is resting with one end on the ground and the other end on the top of a

high wall. A man lifts the lower end of the plank, exerting an upward force of 100 lbs., and then pushes the plank over the wall, releasing it when a length 24 ft. has passed over the wall. If he was at that moment just carried off his feet, find the weight of the man.

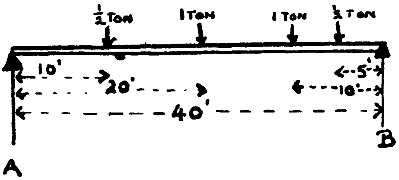


FIG. 55.

11. A beam, 40-ft. span, is loaded, as shown in Fig. 55. Find the reactions of the supports. Check your calculation by means of the link polygon.

12. Describe how you would determine which members of a framed structure are in tension and which are in compression.

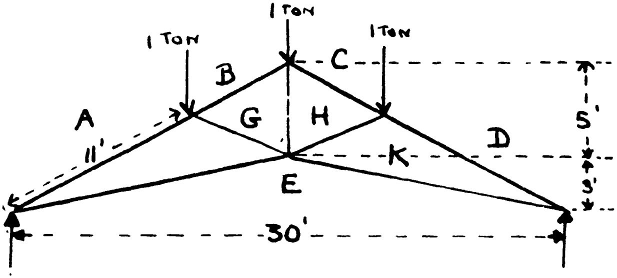


FIG. 56.

13. Fig. 56 shows a loaded roof truss. Find the forces acting in the various members of the truss and state which are in tension and which are in compression.

14. Draw the force diagram for the framed structure shown in Fig. 57, the load AB being 50 lbs.

15. Fig. 58 shows a Warren girder. The length of each member is 5 ft., and a load of 1 ton is placed as shown. Draw the force diagram and find the forces acting in the members, indicating which members are in tension and which are in compression.

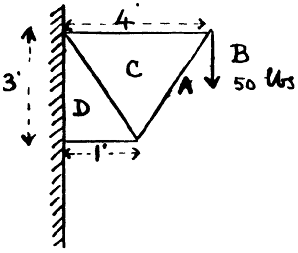


FIG. 57.

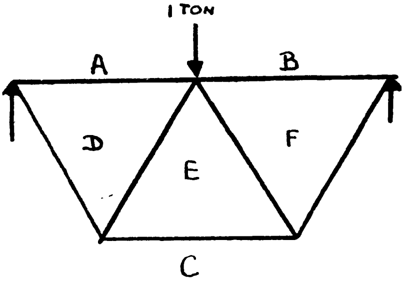


FIG. 58.

CHAPTER V

FRICTION AND LUBRICATION

FRICTION is defined as that part of the mutual action between two surfaces in contact which opposes the sliding of one relative to the other. In Fig. 59 A and B represent two surfaces, A sliding on B. Suppose that all the forces which act on A, except the reaction R of surface B, have a component P which acts in a direction parallel to the surface of contact, then you can easily prove that so long as P does not exceed a certain value, A will remain at rest. The reaction of B will have a component F which is equal in magnitude but opposite in direction to P, and this force F is called friction. As soon as the force P exceeds a certain value, then, of course, one body will slide along the surface of the other.

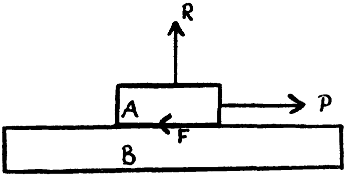


FIG. 59.

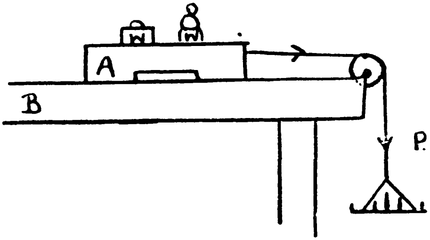


FIG. 60.

EXPERIMENT 10. *To Investigate the Friction between Two Surfaces in Contact.*—Arrange a simple piece of apparatus, as shown in Fig. 60. A being a piece of wood which can be pulled along a horizontal surface B, either by means of a cord passing over a pulley or by means of a spring balance attached to the cord.

In this experiment the weight of A was 1 lb., and a force of 0·55 lb. was just sufficient to move it. Weights were then placed on A, and in each case the pulling force P was noted as follows :—

Weight, W lbs. .	1	1·5	2	2·5	3	4
Pulling force, P lbs.	0·55	0·82	1·1	1·38	1·65	2·2

Plot these results on squared paper (load horizontal) and state conclusions.

Repeat the experiment and note what pulling force P′ is required to keep A moving uniformly along the surface B. Plot the following results of this experiment and state conclusions :—

Weight, W lbs. .	1	1·5	2	2·5	3	4
Pulling force causing uniform motion of A on B, P′ lbs.	0·46	0·7	0·92	1·2	1·38	1·85

Now repeat the above experiments, using the same slider A and the same weights, but having a different area in contact with B. Are your conclusions different from those already obtained ?

Having plotted the readings for the above experiments, you can draw a straight line through the points, and this line passes through the origin, *i.e.*, friction is directly proportional to the load. This means that the ratio $\frac{\text{pulling force}}{\text{load}}$, or $\frac{\text{force of friction}}{\text{normal pressure}}$, is constant, and this constant is denoted by μ and is called the coefficient of friction. You will notice that the slope of the line for the first set of readings above is greater than the slope of the line for the second set of readings, *i.e.*, the static coefficient of friction is greater than the kinetic coefficient of friction.

We can also state that the friction between two surfaces is independent of the speed and also of the area in contact, provided that the speed and loads are not excessive.

Coefficients of Friction (Average Values)

Ash on oak	0·42
Oak on oak	0·35
Wrought iron on oak	0·61
Cast iron on oak	0·49
Cast iron on cast iron	0·15
Cast iron on wrought iron	0·14
Metal on metal (average), dry	0·16
Metal on metal (average), wet but clean	0·30
Metal on metal (average), wet and greasy	0·15
Leather on metal, dry	0·55
Leather on metal, wet	0·35
Leather on metal, greasy	0·25
Leather on wood	0·25 to 0·35

Example 1.—A piece of iron weighing 10 lbs. rests on a horizontal surface and the coefficient of friction between the surfaces is 0·3. How much work will be done when the iron is made to slide through 5 ft. ?

$$\mu=\frac{\text{pulling force}}{\text{load}},\ \textit{i.e.},\ 0{\cdot}3=\frac{\text{pulling force}}{10},$$

or

$$\text{pulling force}=3 \text{ lbs.}$$

$$\text{Work done}=\text{force}\times\text{distance}=3\times5=15 \text{ ft.-lbs.}$$

Consider a weight W which can be moved along a horizontal surface by applying a force P (Fig. 61). When the weight is just on the point of moving, the value of P will be equal in magnitude but opposite in direction to the force of friction F. In Fig. 61 AB is drawn to represent W in magnitude and direction and AD is made equal to F when the body is on the point of moving in the direction of the pulling force P. If the pulling force is less than that required to move the weight, then the weight will be under the action

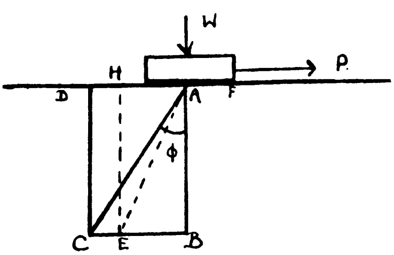


FIG. 61.

of two forces AB and, say, a force represented by AH, and by the parallelogram of forces AB and AH will have a resultant which is represented in magnitude and direction by AE. In the limiting case, *i.e.*, when the body just moves, AH will be increased to AD, and the resultant will then be AC, which makes an angle ϕ, as shown, with AB.

This angle ϕ is known as the angle of friction, and it indicates the inclination measured from the horizontal at which one surface will just slide down another after an initial start. In the above figure CBA is a right-angled triangle, and $\frac{CB}{BA}=\tan\phi$. But BC represents F the force of friction and AB represents the weight W, so that we can say that $\frac{CB}{BA}=\frac{F}{W}=\tan\phi=\mu$. In words this means that one surface will just slide down another when the surface is inclined at an angle such that its tangent is equal to the coefficient of friction.

Example 2.—A force of 6 lbs. will just move a weight of 15 lbs. along a horizontal surface. What is the coefficient of friction ? At what angle should the plane be tilted so that the weight may just slide down the surface ?

$$\mu=\frac{\text{pulling force}}{\text{load}}=\frac{6}{15}=0{\cdot}4.$$

From trigonometrical tables we find that the angle whose tangent is 0·4 is 21° 48′, and this is the angle at which the plane must be tilted.

EXPERIMENT 11. *To find the Coefficient of Friction of a Screw-jack.*—A screw-jack is represented at (*a*) (Fig. 62), and will be considered further in the next chapter. It consists of a circular table A, radius R, attached to a square threaded screw B (pitch p), which fits into a base c. A heavy load W is lifted by means of an effort E, as shown.

When the effort turns the table through one revolution the load will be lifted through a distance equal to the pitch of the thread. If the diameter of the screw thread is d, and α equals its inclination to the horizontal, then $\tan\alpha=\frac{p}{\pi d}$, as shown at (*b*) (Fig. 62), which figure also shows ϕ the angle of friction. From these particulars we are able to construct the triangle of forces (*c*) (Fig. 62), from which it will be seen that $\frac{E}{W}=\tan(\alpha+\phi)$ where E is the effort applied horizontally and W is the load lifted.

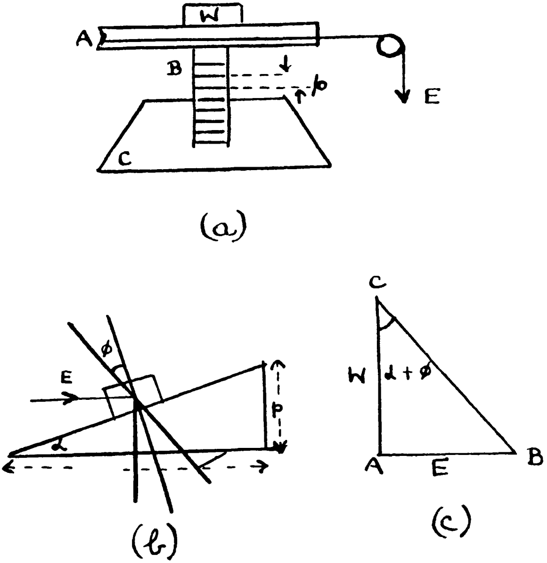


FIG. 62.

The following table shows the effort E lbs. required to lift a load W lbs. :—

W lbs. .	11	16	21	26	31	36	41	46
E lbs. .	0·6	0·9	1·2	1·5	1·8	2·1	2·4	2·7

These results are shown plotted in Fig. 63, and as the line obtained does not pass through the origin we draw a line parallel to it and passing through the origin. On this line consider any load and the corresponding effort, say W=32·5 lbs. and E=2 lbs.

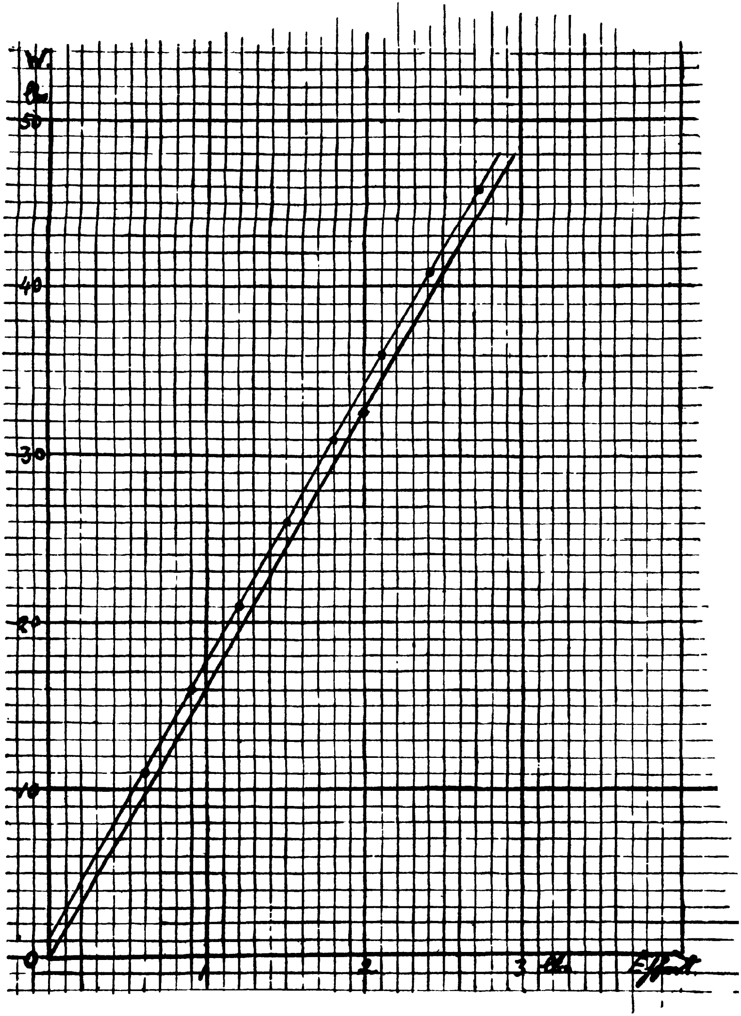


Fig. 63.

In the screw-jack to which the above readings refer the radius of the table $R=4$ in., the diameter of the screw thread $d=1\cdot5$ in., and the pitch of the thread $p=\frac{1}{2}$ in.

Torque$=ER=P\frac{d}{2}$ where $P=$effort applied at the circumference of the screw thread, *i.e.*, $2\times4=P\times\frac{3}{4}$, or $P=\frac{32}{3}$ lbs., $\frac{P}{W}=\tan(a+\phi)$, and the student who has studied trigonometry will be able to prove that $\tan(a+\phi)=\frac{\tan a+\tan\phi}{1-\tan a\tan\phi}$.

Therefore $$\frac{32}{3\times32\cdot5}=\frac{32}{97\cdot5}=0\cdot328=\frac{\tan a+\tan\phi}{1-\tan a\tan\phi},$$

and since $$\tan a=\frac{\text{pitch}}{\pi d}=\frac{\frac{1}{2}}{\frac{22}{7}\times\frac{3}{2}}=0\cdot106,$$

we have
$$0\cdot328=\frac{0\cdot106+\tan\phi}{1-0\cdot106\tan\phi},\ \text{or}\ 1\cdot035\tan\phi=0\cdot222,$$

whence $\tan\phi$ or μ the coefficient of friction$=0\cdot215$.

Check this result by considering any other point on the graph.

There are cases where it is necessary to have a large amount of friction between two surfaces in contact. For example, if it were not for the friction between the soles of our boots and the road, we should be unable to walk. In the case of ice or other smooth surface there is very little friction, and you will all have experienced a difficulty when walking along such surfaces. Without friction a belt would be useless for driving a pulley, and a method other than braking a moving vehicle would have to be devised in order to stop the vehicle.

Energy may be transmitted from one shaft to another in line with it by means of a friction cone-clutch, which is illustrated in Fig. 64. A pulley C is keyed to a shaft A and D is a cone which can slide along the shaft B, a feather key fixed into a groove in shaft B enabling D to slide along the shaft by means of a lever which fits into the groove in D.

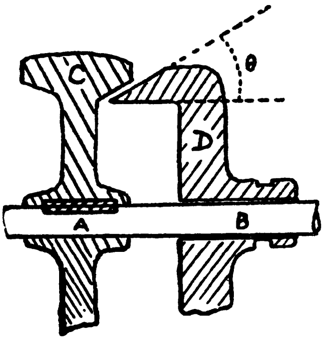


FIG. 64.

As soon as the slant faces are in contact the shaft B will be driven by the pulley on shaft A. The angle θ, shown in the diagram (Fig. 64), must not be greater than the angle of friction for the surfaces in contact, *i.e.*, knowing the coefficient of friction for the two surfaces of C and D, the included angle of the cone 2θ may be obtained.

Example 3.—The pressure on a horizontal shaft 6 in. in diameter is 3 tons, and the shaft rotates at 100 revs. per min. How many heat units will be generated per minute if the coefficient of friction is 0·02 and 778 ft.-lbs. of work= 1 heat unit ?

$$\mu=\frac{\text{force of friction}}{\text{normal pressure}},\ i.e.,\ 0{\cdot}02=\frac{\text{force}}{6720},$$

or $$\text{force}=0{\cdot}02\times6720=134{\cdot}4\text{ lbs.}$$

$$\text{Distance travelled per minute}=\pi\times0{\cdot}5\times100=157\text{ ft.}$$

$$\text{Work done per minute}=\text{force}\times\text{distance}=134{\cdot}4\times157$$
$$=21100\text{ ft.-lbs.}$$

Therefore

$$\text{heat generated per minute}=\frac{21100}{778}=27{\cdot}1.$$

The student will be aware of other cases where friction is an advantage, and he will also realise that in most machines it is a disadvantage, as it generates heat and causes loss of energy.

In the above example the heat generated could be reduced if the friction were reduced, and this would reduce the wear and tear on the machine. The reduction of friction in machines and in various parts of machines brings us to another important section of our work, and that is lubrication.

For nearly all machines and engines the question of lubrication is of the utmost importance, but through carelessness it is very often neglected. A lubricant forms a film between two surfaces in contact and tends to reduce friction. Gear-boxes, crank-cases, and other parts of a machine which run in an " oil-bath " should periodically have the dirty oil drained off. They should then be thoroughly cleaned by means of paraffin oil and then be recharged with good lubricating oil. When in doubt as to whether a machine requires oil it is better to apply it, as over-lubrication is an error on the right side, if an error at all. Erratic working of a machine, overheating, and knocking are signs that more lubricating oil is wanted.

Oils are generally classified as animal, vegetable, or mineral, according to their source, and it is evident that a lubricating oil which is suitable for one machine may be quite unsuitable for use on another type of machine. For example, for main bearings it is usual to employ a grease made from certain oils and solidified by means of soap or wax, whereas a light mineral or vegetable oil would be used in the case of fast-running shafts. For the working parts of a machine such as a bicycle pure graphite mixed with a light mineral oil forms an efficient lubricant, but it would be useless in the case of the piston of a petrol engine which works at a high speed and at a high temperature.

In dealing with oils, certain properties have to be specified, depending on the purpose for which they have to be used. One of these properties is specific gravity, which we shall deal with in a later chapter. Another property is "viscosity," *i.e.*, its thickness or resistance to flow. An experimental method of determining this property is beyond the scope of this work, but the student who continues his study of engineering will determine it later by means of Redwood's viscometer. What is called the " flash-point " of a lubricant is the temperature at which it will give off an inflammable vapour, and this also will be determined at a later stage in the student's career by means of an apparatus known as Gray's tester. It may be mentioned here that the flash-point should be high, and especially in the case of oils which are used at high temperatures.

The following table shows the above - mentioned properties in the case of one or two common oils :—

Oil.	Specific Gravity at 60° F.	Viscosity.		Flash-point. ° F.
		70° F.	180° F.	
Vacuum A . . .	0·903	694	62	421
Vacuum B . . .	0·892	4,400	183	486
Vacuum BB . .	0·895	2,502	120	432
Castor oil . . .	0·962	3,840	138	492
Olive oil . . .	0·915	310	150	457

It can be proved experimentally that when one body rolls along another the rolling friction is less than sliding friction, and that rolling friction is directly proportional to the load and, within limits, is inversely proportional to the diameter of the roller. In the case of " ball-bearings " specially hardened steel spheres are held in position by what is termed a " ball-race." As the shaft or wheel axle rotates, the balls will roll along a hardened surface and so reduce the friction which would otherwise be present, and efficient lubrication will reduce the friction still further.

We can now consider one or two points which should receive attention in order that lubrication should be efficient.

In dealing with machines the name " bearing " is given to that part which supports or influences the motion of some moving part. We shall consider a fixed bearing which supports a rotating shaft or journal, but the student will realise that it is not always necessary for a bearing to be fixed, as, for example, in the case of a crankpin bearing of a connecting-rod of a locomotive. Bearings may be termed radial, thrust, or guide, according to the way in which they control the moving parts of a machine, and in order that they may be efficient should be designed in such a way that it is possible for a thin oil film to form between the moving parts. The formation of this film of oil is illustrated in Fig. 65, which is reproduced with permission from No. 19 of the Gargoyle Technical Series, issued by the Vacuum Oil Co. Ltd.

In this diagram four views are given showing the journal in its bearing, and the load on the journal acts in a downward direction. In Fig. 65 (*a*) the journal is at rest and the load is sufficient to force the lubricating oil from the areas in contact. When the journal rotates in the direction of the arrow it has a tendency to roll in the bearing, and in doing this it will make a new line of contact, as shown at D ((*b*), Fig. 65).

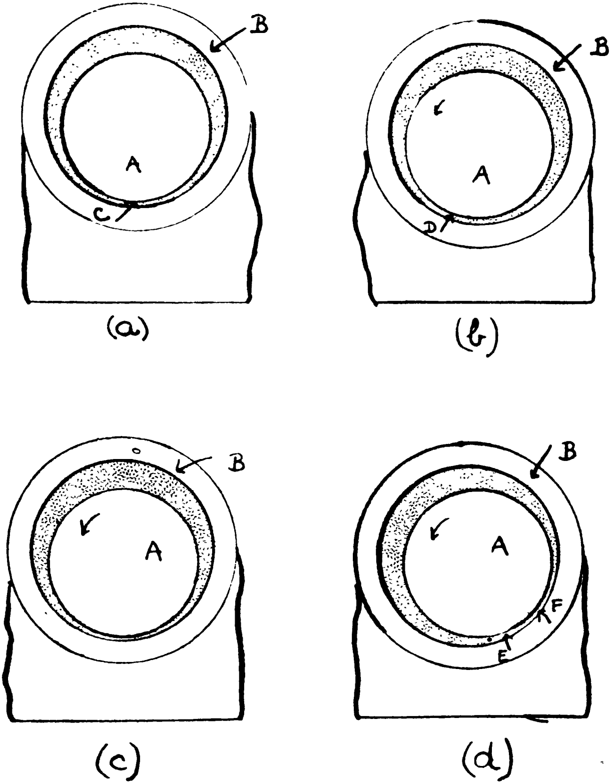


FIG. 65.

In this operation a small quantity of oil will be trapped, and so a thin film will be formed which separates the surfaces in contact. As the journal continues to rotate, some of the oil will adhere to it and will be carried round into the supporting film, which thus increases and lifts the journal slightly, as shown at (*c*) (Fig. 65). The final position of the rotating journal is shown at (*d*) (Fig. 65), and it has been proved by experiment that when the speed of the journal is high and the load is not excessive the greatest pressure in the oil film is at the point marked E.

This final position of the journal may be explained as follows :—

First of all, its weight tends to fix its position as low as possible in the bearing. The oil film which the rotating journal carries along, to the left at the top and to the right at the bottom, lifts it slightly, and this operation is facilitated by the large clearance at the top and the small clearance at the bottom, the latter retarding the flow of oil. There will now be a large pressure on the left of the bearing which, in addition to lifting the journal, will displace it slightly to the right until the system is in equilibrium.

It should be noticed that when the journal is rotating, its centre and that of the bearing do not coincide, and that the point of least clearance is in the neighbourhood of F ((*d*), Fig. 65).

Finally, when the load is increased beyond a certain maximum the oil film will fail to separate the journal and its bearing, and in this case lubrication is impossible, and this, of course, means excessive friction and wear and tear. Slow speeds, high temperatures, and poor quality oils will produce the same results.

In concluding this chapter it might be mentioned that the oldest and still frequently used method of applying a lubricant is by means of the hand oil-can. At its best this method is very irregular, wasteful, and generally inefficient. Where possible the student should examine the different types of lubricator which are on the market, make simple free-hand sketches of them, and describe their methods of working.

CHAPTER VI

SIMPLE MACHINES AND MECHANISMS

A MACHINE may be defined as an arrangement which takes in a supply of energy in some particular form, modifies it, and transmits it in some other more suitable form, and we can say that a mechanism is an essential part of a machine. For example, a supply of energy may be put in at what is called the driving end of the machine, and it will then be transmitted through what is termed a " train of mechanism " to the driven end of the machine. During the transmission the energy will be modified either in magnitude or in direction, or in both, depending on the object for which the machine has been designed.

The simplest machine of all is, of course, the lever, which consists of a rod pivoted about a point called the fulcrum. An effort applied at one part of the rod overcomes a resistance or lifts a load applied at some other part of the rod. If we know any three of the four quantities, load, effort, distance of load from fulcrum, and distance of effort from fulcrum, we can apply the principle of moments to determine the unknown term.

In the case of a lever, if the fulcrum is between the points of application of the effort and the resistance, it is known as a lever of the first class; if the resistance is between the fulcrum and the effort, it is known as a lever of the second class; if the effort is between the fulcrum and the resistance, it is known as a lever of the third class. Examples of the three classes of lever are illustrated in Fig. 66, A representing the handle of a pump, B the front-wheel brake of a bicycle, and C the treadle of a lathe. In all three cases, if E=efforts (lbs.), R=resistance (lbs.), a=distance of effort from the fulcrum, and b=distance of the resistance from the fulcrum, we have $Ea=Rb$, so that given any three of these quantities we can find the fourth.

Fig. 67 illustrates a mechanism known as the lever safety-valve, which is one of the fittings used on steam boilers. A weight W_3 is hung on the lever in such a position as to allow the steam to lift the valve when the pressure of the steam reaches what is called the "blow-off" pressure. In the diagram as sketched L ft. is the length of the lever, which we will assume to be uniform, and W_3 is a weight hung at the end of the lever when the steam is on the point of blowing off. The weight of the lever is W_2, and as the lever is uniform this weight acts half-way along its length, *i.e.*, at a distance $\frac{L}{2}$ ft. from the fulcrum F. The weight of the valve is W_1, and it is fixed at a distance l ft. from F. If the diameter of the

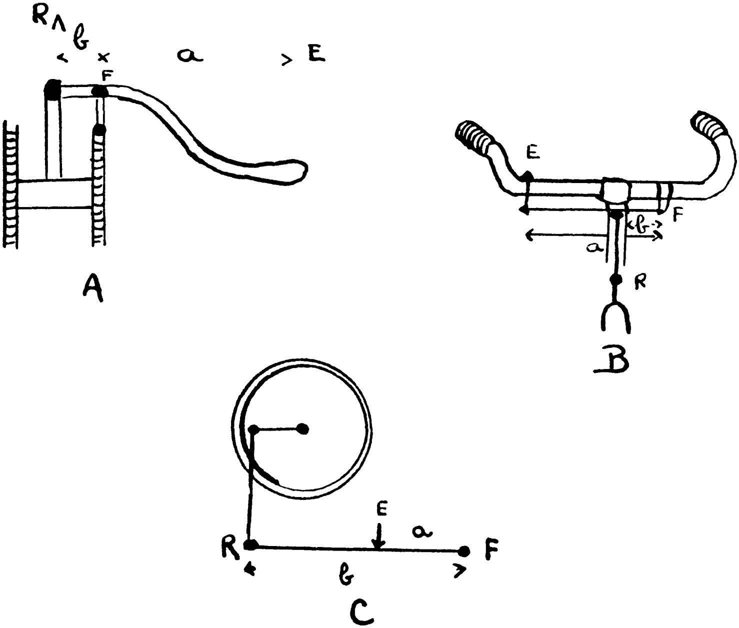


Fig. 66.

valve is D in., and P lbs. per sq. in. is the steam pressure, we have, taking moments round F,

$$W_3L+W_2\frac{L}{2}+W_1l=P\times 0\cdot 7854D^2l,$$

from which we can determine any one quantity if the remaining quantities are known.

Example 1.—The diameter of a safety-valve is 2 in. and the length of the lever is 1 ft. 8 in. If the distance between the fulcrum and the centre line of the valve is 4 in. and the weight on the end of the lever is 40 lbs., find the steam pressure when on the point of blowing off. Neglect the weight of the lever and that of the valve.

Neglecting the weight of the lever and of the valve, the above formula becomes $W_3L=P\times 0\cdot 7854D^2l$, and substituting the given values, we have

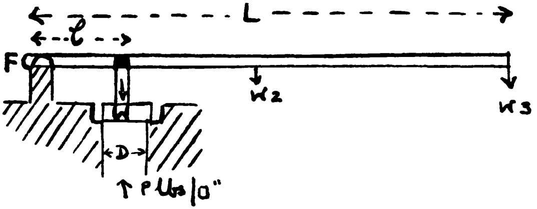


FIG. 67.

$$40\times 20=P\times 0\cdot 7854\times 4\times 4,$$

whence $$P=\frac{40\times 20}{\cdot 7854\times 160}=63\cdot 6 \text{ lbs. per sq. in.}$$

EXPERIMENT 12. *Crank and Connecting-rod Mechanism.*—The object of this experiment is to study the linear displacement of a steam engine piston in relation to the angular movement of the crank, and the apparatus is illustrated in Fig. 68.

The flywheel is divided into hundredths of a revolution, and as it is rotated through, say, every five divisions from the inner dead-centre, the distance, X in., moved through by the piston is noted.

The following table shows the distance moved through

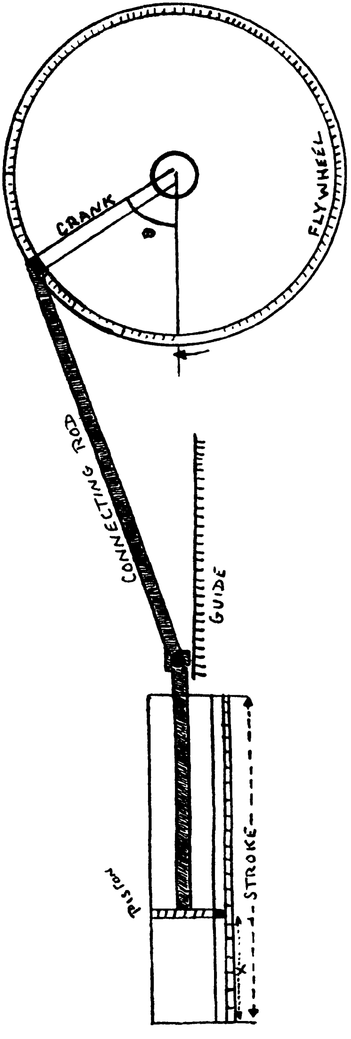


FIG. 68.

by the piston for one complete revolution of the crank. Complete the table, assuming that the crank rotates uniformly at 60 revs. per min., then plot columns 2 and 3, 6 and 3, and 6 and 2, and state your own conclusions :—

	1	2	3	4	5	6
	θ $\frac{1}{100}$ Rev.	X In.	Time T Secs. from Start.	Increase in Distance.	Increase in Time.	Velocity of Piston $= \frac{\text{Increase in Distance}}{\text{Increase in Time}}$.
						In. per Sec.
Out Stroke.	0	0·0	0·0	0·0	0 0	0
	5	0·3	0·05	0·3	0·05	6
	10	1·1	0·10	0·8	0·05	16
	15	2·45	0·15	...	...	...
	20	4·0	...	...	...	...
	25	5·6	...	...	...	...
	30	7·1	...	...	...	...
	35	8·35	...	...	...	...
	40	9·25	...	...	...	...
	45	9·8	...	...	...	...
	50	10·0	...	...	...	...
Return Stroke.	55	9·8	...	...	...	...
	60	9·3	...	...	...	...
	65	8·45	...	...	...	...
	70	7·25	...	...	...	...
	75	5·8	...	...	...	...
	80	4·2	...	...	...	...
	85	2·6	...	...	...	...
	90	1·25	...	...	...	...
	95	0·3	...	...	...	...
	100	0·0	...	...	...	...

During his practical training the student will deal with cutting and shaping machines in which the outward or cutting stroke is performed at a slower speed than the return or idle stroke, and Fig. 69 illustrates the principle of obtaining this quick-return motion.

The mechanism consists of a crank at one end of which is fitted a block which slides in a slotted lever (see A, Fig. 69).

This slotted lever is hinged at a point P, and as the crank rotates, the lever oscillates about this point. The free end of this lever is connected to the sliding ram by means of a connecting-rod, as shown, and on the end of the ram the cutting tool is fixed. In the position as sketched the cutting tool will be at the end of its travel, and the beginning of its stroke will be when the slotted lever is in the position P*c*, *i.e.*, at each end of the stroke the crank will be at right angles to the lever. Assuming the crank to rotate uniformly in a clockwise direction, the time taken to perform the cutting stroke will be the time required for the crank to move through the large arc *cda*, and the return idle stroke will be completed in the time taken by the crank to move through the small arc *abc*.

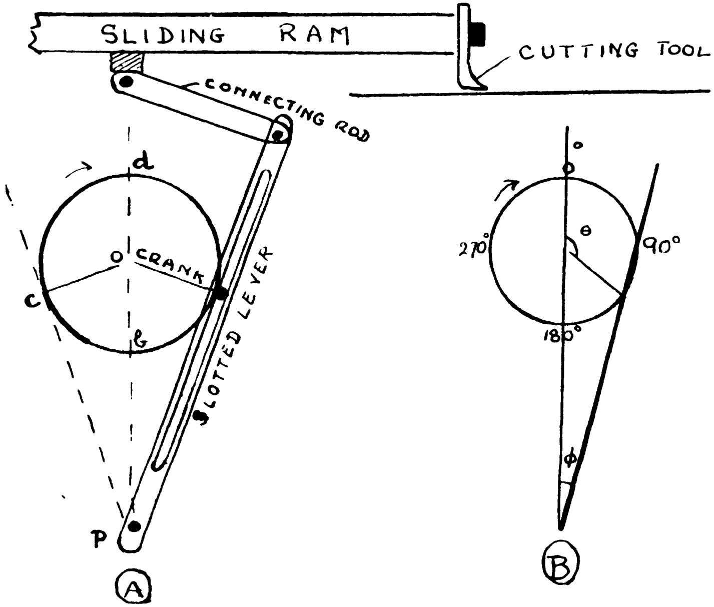


FIG. 69.

As shown at A (Fig. 69) $\overset{\wedge}{coa}=220°$, so that $\overset{\wedge}{aoc}=140°$. If the crank rotates uniformly at 60 revs. per min., the cutting stroke will be performed in $\frac{220}{360}=0{\cdot}61$ sec., and it will return in $\frac{140}{360}=0{\cdot}39$ sec., so that the ratio $\frac{\text{time to perform cutting stroke}}{\text{time of return stroke}}$

$=\frac{0\cdot61}{0\cdot39}$, or 1·571 : 1. It is obvious that since the time required to perform the return stroke is less than that on the cutting stroke the average speed of the ram will be greater in the former case.

Exercise.—Reproduce the diagram shown at B (Fig. 69), but to a larger scale. When the crank is in the position marked 0°, the slotted lever will also be in the same position. Let the crank rotate through an angle θ 15° at a time for one complete revolution. Note the corresponding angle turned through by the slotted lever ϕ. Plot θ and ϕ for one revolution and state conclusions.

Example 2. — In a quick return motion for a shaping machine the length of the slotted lever is 8 in. and the crank is 1-in. radius. If the distance between the crank centre and the pivot of the slotted lever is 5 in., determine the ratio $\frac{\text{average return speed}}{\text{average cutting speed}}$ and also the stroke of the cutting tool.

In Fig. 70 AB and AC represent the extreme positions of the slotted lever, so that BC represents the stroke of the cutting tool.

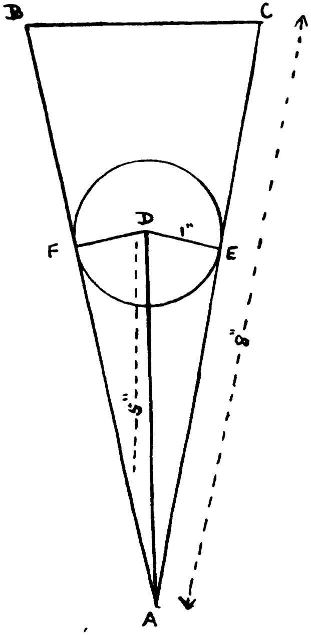


Fig. 70.

In this diagram $\frac{DE}{DA}=\frac{1}{5}=0\cdot2=\sin D\hat{A}E$, therefore from the mathematical tables we find that $D\hat{A}E=11\cdot5°$ (approx.). $A\hat{D}E$ will therefore be $90°-11\cdot5°=78\cdot5°$, so that the angle turned through by the crank on the return stroke, *i.e.*, $E\hat{D}F$, will be 157°. During the cutting stroke FDE will be $360° - 157° = 203°$.

Therefore

$$\text{Ratio } \frac{\text{average return speed}}{\text{average cutting speed}} = \frac{203}{157} = 1\cdot 3 \text{ (nearly).}$$

In the triangle ABC we have $B\hat{A}C = 23°$.

$$A\hat{B}C = \frac{180 - 23}{2} = 78\cdot 5°,$$

so that by trigonometry we can say

$$\frac{\text{BC (stroke of cutting tool)}}{\sin 23°} = \frac{8}{\sin 78\cdot 5°},$$

i.e.,

$$\frac{BC}{0\cdot 3907} = \frac{8}{0\cdot 9799},$$

whence $BC = 3\cdot 2$ in. (approx.).

A convenient method of converting rotary motion into a reciprocating motion is to employ a form of mechanism known as a cam. A simple form of cam is illustrated in Fig. 71, where C is the cam fixed on a shaft A. The rod B will move in the guide E, and friction between the rod and the surface of the cam is reduced by means of a small roller D, sometimes a small spring being used to keep D in contact with the edge of the cam. Fig. 72, kindly supplied by the Morris Oxford Press Ltd., shows the camshaft and cams which operate the valves in the cylinders of a motor car engine.

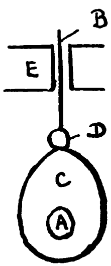


Fig. 71.

The shape of a cam will, of course, depend on the motion it has to provide, and as the opportunity arises the student should examine and sketch and describe the various forms.

In this work the student need only be concerned with a simple type of cam which gives a definite motion to a slider in contact with it. The determination of the shape of a cam can best be explained by means of an example.

Example 3.—Design the outline of a heart cam to give a uniform rise and fall of 1 in. to a slider in contact with it. Diameter of roller on the end of the slider=$\frac{1}{4}$ in., and the least distance between the centres of the roller and camshaft=$\frac{3}{4}$ in.

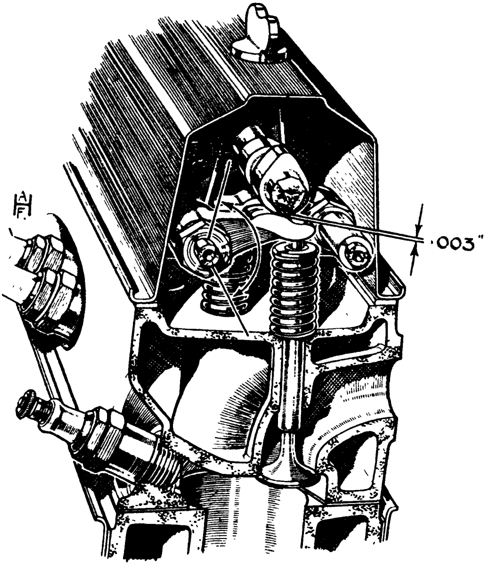


Fig. 72.

The outline design of the above cam is shown in Fig. 73, the construction being as follows :—

Draw a circle any radius with centre O, this point being the centre of the camshaft. Now draw a vertical line through O and along this line mark off a distance OC=$\frac{3}{4}$ in., this being the given distance between the centres of the camshaft and roller. From C along the vertical line mark off a distance C6=1 in., the given rise of the slider, and divide C6 into six equal parts, as shown. Next draw the radial lines from O, making the angle between each of them=30°. Now, with centre O and radius O1 measured along the vertical line, draw an arc cutting the two radial lines on each side of the vertical in the points marked 1. Again, with centre O and radius O2 measured along the vertical, draw arcs cutting the second radial lines on each side of the vertical at the points marked 2, and repeat this construction for each point of division measured along the vertical line. If we join the points of intersection of these arcs and radial lines, we obtain the curve shown by the dotted line, and this curve represents the path of the centre of the roller. The required outline of the cam will be the full line curve, as shown, this curve being parallel to the dotted line curve and $\frac{1}{8}$ in. from it.

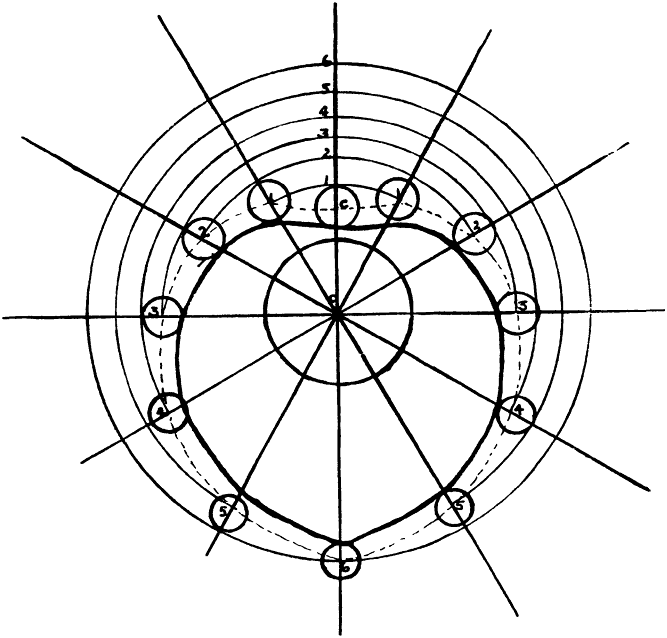


FIG. 73.

Exercise.—Design the outline of a cam to give a uniform rise of 1·5 in. to a slider during one-third of a revolution, followed by a rest for one-third of a revolution, and then a uniform fall for the remainder of the revolution. Diameter of the roller in contact with the cam $=\frac{1}{4}$ in., and the least distance between the centres of the camshaft and roller $=1\frac{3}{4}$ in.

In dealing with machines certain terms are used with which the student should be familiar, and we will discuss these terms with reference to a machine known as the wheel and axle.

This machine, which is used for lifting weights, is illustrated in Fig. 74. The radius of the wheel is R, and that of the axle, which is fixed to the wheel, is *r*. An effort E is applied at the end of a rope which is wound on the wheel, and a load W is lifted by being fixed to the end of a rope which is wound on the axle, these two ropes being wound in opposite directions.

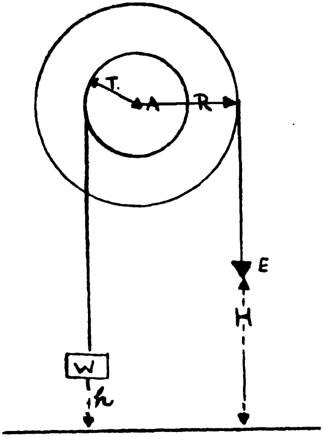


FIG. 74.

Suppose that as the effort moves downwards through a distance H the load is lifted upwards through a distance *h*, then the ratio $\frac{H}{h}$, *i.e.*, $\frac{\text{distance moved by effort}}{\text{distance moved by load}}$, we call the velocity ratio of the machine. The ratio $\frac{\text{load lifted}}{\text{effort applied}}=\frac{W}{E}$ is defined as the force ratio or mechanical advantage, while the efficiency of the machine would be defined as the ratio $\frac{\text{work got out of the machine}}{\text{work put in the machine}}$. We shall see presently that the efficiency of a machine may also be given as the ratio $\frac{\text{mechanical advantage}}{\text{velocity ratio}}$.

To find the mechanical advantage of the wheel and axle in terms of their radii.

When the system is in equilibrium, *i.e.*, when the effort is just sufficient to balance the load, we have, taking moments round the centre,

$$ER=Wr, \text{ or } \frac{W}{E}=\frac{R}{r},$$

i.e., $$\text{mechanical advantage}=\frac{\text{load}}{\text{effort}}=\frac{\text{radius of wheel}}{\text{radius of axle}},$$

and it should be noticed that the mechanical advantage may be increased either by increasing the radius of the wheel or by decreasing the radius of the axle, both, however, within limits.

Rope Pulley Tackle

Fig. 75 represents an arrangement by means of which a load is raised by a rope passing round a system of pulleys. After passing round all the pulleys the rope is finally attached to the lower part of the tackle, and this part of the rope which is attached to the tackle will move the same distance as the load to be lifted. As sketched in the diagram the part of the rope at which the effort is applied will move twice as far as the load, so that the total distance moved by E will be $2+1$ or three times the distance moved by W, *i.e.*, the velocity ratio of the tackle will be equal to the number of pulleys used.

To find the mechanical advantage of the system.

Suppose that there are N ropes attached to the lower part of the tackle, then NE will support a load $W+w$ where w is the weight of the tackle, *i.e.*, $NE=W+w$.

If w is small compared with the load lifted W, then we can say that $NE=W$, or mechanical advantage$=\frac{W}{E}=N$, *i.e.*, it is equal to the number of ropes in the lower part of the tackle.

Fig. 76 shows a diagrammatic representation of what is known as Weston's differential pulley. In the top block there are two pulleys of different diameters, and an endless chain passes round the pulleys, as shown. The load lifted W is attached to a pulley in the lower block, so that each part of the chain which supports the pulley and load will carry half the total weight, *i.e.*, $\frac{W}{2}$.

To find the mechanical advantage of this system.

Let $R=$radius of the large pulley and $r=$that of the smaller pulley, and let the effort E just support the load W.

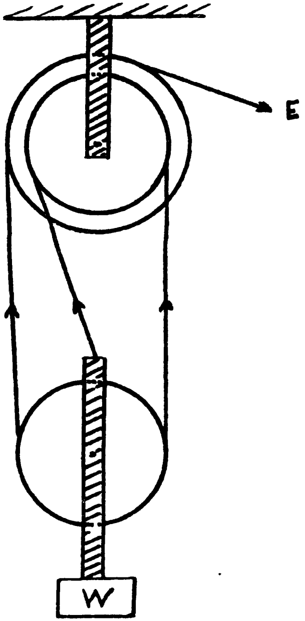


FIG. 75.

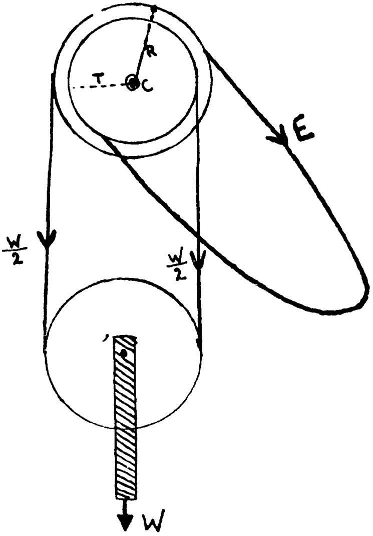


FIG. 76.

Taking moments round the centre C, we have

$$ER + \frac{W}{2}r = \frac{W}{2}R,$$

or
$$ER = \frac{W}{2}(R - r) = \frac{W(R - r)}{2},$$

i.e.,
$$\text{mechanical advantage} = \frac{\text{load}}{\text{effort}} = \frac{W}{E} = \frac{2R}{R - r}.$$

At this stage it will be convenient to study what is known as the " law of a machine," and we can do this by considering the graph in Fig. 63, Chapter V., which shows the efforts required to lift various loads by means of a screw-jack.

The graph obtained is a straight line, and the student will no doubt be familiar with the fact that a straight line is represented by the equation $y=ax\pm b$, where x and y are the horizontal and vertical axes respectively, a is the tangent of the angle that the line makes with the horizontal axis, and b is the distance from the origin where the line cuts the vertical axis.

In Fig. 63, since the load W is plotted vertically and the effort E is plotted horizontally, the law of the machine will be $W=aE+b$. To determine what load can be lifted by a given effort, or what effort will be necessary to lift a given load, we must first of all find numerical values for the constants a and b. To do this consider any two points on the graph or from the tabulated values. When W=11 lbs., E=0·6 lb., and when W=36 lbs., E=2·1 lbs. We therefore have

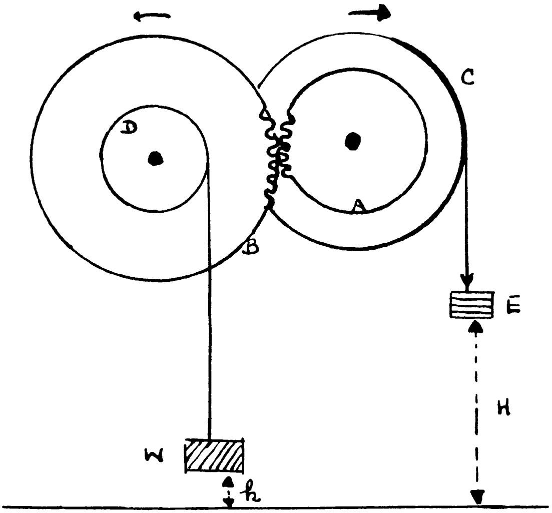


FIG. 77.

$$11=0{\cdot}6a+b \quad . \quad . \quad . \quad . \quad (1)$$

and

$$36=2{\cdot}1a+b \quad . \quad . \quad . \quad . \quad (2)$$

Solving these two equations we find that $a=16\frac{2}{3}$ and $b=1$, *i.e.*, the law of the machine is $W=16\frac{2}{3}a+1$, or $3W=50E+3$. Using this result we find that an effort of 1·5 lbs. will lift a load of 26 lbs., and we can also determine any other load or effort as may be required.

Fig. 77 illustrates a simple type of lifting crab in which two wheels A and B are in gear. An effort E is applied at the end of a rope which passes round a pulley C keyed to the same shaft as wheel A. This effort lifts a load W attached to a rope which is wound round the drum D keyed to the same shaft as the wheel B.

Suppose that the effort E moves through a distance H in the same time that the load W is lifted through a height h, then the velocity ratio of the machine V would be $\frac{H}{h}$. If the effort E is just sufficient to lift the load W, then the mechanical advantage of the machine will be given by the ratio $\frac{W}{E}$.

If we had an ideal machine, *i.e.*, one working without loss due to friction, etc., then a larger load than W, say W′, could be lifted by the application of the same effort E. In this case work done by the effort would be equal to the work done on the load, *i.e.*, $EH=W'h$, or $W'=E\frac{H}{h}=EV$. In an actual machine there is a loss due to friction, *i.e.*, friction reduces the load lifted from an amount W′ to an amount W. Therefore loss due to friction $F=W'-W=EV-W$.

Work done on the machine$=EH$, and work given out by it$=Wh$, so that efficiency$=\frac{Wh}{EH}$. But velocity ratio $V=\frac{H}{h}$, so that we can therefore state that

$$\text{Efficiency}=\frac{\text{mechanical advantage}}{\text{velocity ratio}}.$$

From this it is easy to see that in an ideal machine when the efficiency is 100 per cent. the mechanical advantage is equal to the velocity ratio.

Example 4.—The velocity ratio of a machine used for lifting loads is 40, and an effort of 15 lbs. is required to lift a load of 180 lbs. Determine the mechanical advantage, the effect of friction, and the efficiency of the machine at this load.

$$\text{Mechanical advantage}=\frac{\text{load lifted}}{\text{effort applied}}=\frac{180\text{ lbs.}}{15\text{ lbs.}}=12.$$

$$\text{Effect of friction}=\text{effort}\times\text{velocity ratio}-\text{load lifted}$$

$$=15\times40-180=420.$$

$$\text{Efficiency}=\frac{\text{mechanical advantage}}{\text{velocity ratio}}=\frac{1200}{40}=30\text{ per cent.}$$

EXPERIMENT 13. *To show how the Effort, Effect of Friction, Mechanical Advantage, and Efficiency of a Machine used for Lifting Loads vary with the Load Lifted.*—In this experiment we can use the figures given in Experiment 11 relating to a screw-jack. The apparatus is shown at (*a*) (Fig. 62,) and when the effort E turns the table A through one complete revolution the load will be lifted through a distance equal to the pitch of the screw thread. The radius of the table is 4 in. and the pitch of the screw is ½ in., so that the velocity ratio V

$$=\frac{2\pi R}{p}=\frac{2\,.\,\pi\,.\,4}{\frac{1}{2}}=50\cdot27.$$

The loads and their corresponding efforts are as follows :—

Load, W lbs. . .	11	16	21	26	31	36	41	46
Effort, E lbs. . .	0·6	0·9	1·2	1·5	1·8	2·1	2·4	2·7
Effect of friction F. .	19·6	...	...	...	...	...	...	...
Mechanical advantage	18·3	...	...	...	...	...	...	...
Efficiency per cent. .	36·4	...	...	...	...	...	...	...

Dealing with the first load and effort, we have for the effect of friction $F=EV-W$, *i.e.*, $F=0\cdot6\times50\cdot27-11=19\cdot6$.

$$\text{Mechanical advantage}=\frac{11}{0\cdot6}=18\cdot3.$$

$$\text{Efficiency }\%=\frac{\text{mechanical advantage}\times100}{\text{velocity ratio}}=\frac{183000}{5027}=36\cdot4.$$

Complete the above table, then show, graphically, the following relations, viz.: (1) load and effort, (2) load and friction, (3) load and mechanical advantage, (4) load and efficiency.

Curves similar to the above would be obtained with other types of machine, and where possible the student should carry out a test.

Example 5.—How much work will be done in pumping 500 gals. of water to a height of 50 ft.? Calculate the horse-power developed if this work is done in 10 mins. If the efficiency of the pump is 60 per cent., calculate what horse-power must be supplied.

Work done=force × distance=5000 lbs. × 50 ft.=250000 ft.-lbs.

$$\text{Work done per minute} = \frac{250000}{10} = 25000.$$

$$\text{Therefore} \qquad \text{horse-power} = \frac{25000}{33000} = 0{\cdot}757.$$

Since the efficiency of the pump is 60 per cent., horse-power which must be supplied $= \frac{0{\cdot}757 \times 100}{60} = 1{\cdot}26.$

FIFTH SET OF EXAMPLES

1. What is the " coefficient of friction " ?

A variously loaded slider was moved slowly but uniformly over a horizontal surface, and the different total weights W of the cradle and the corresponding horizontal forces F necessary to move it were as follows :—

W lbs. . .	10	15	20	25	30	35
F lbs. . .	1·9	3·1	4·1	4·9	6	7·1

Plot a graph connecting F and W, and determine the coefficient of friction for the surfaces.

What force would be necessary to move the cradle when loaded to 27 lbs.? U.L.C.I.

2. A body weighing 10 lbs. is moved through 15 ft. on a horizontal surface. If the coefficient of friction between the

surfaces is 0·2, how much work will be done in moving the body?

3. A shaft 6 in. in diameter rotates at 210 revs. per min. and the load on the shaft is 1 ton. If the coefficient of friction between the shaft and its bearing=0·02, calculate the horse-power absorbed in driving it.

4. " Oil is cheaper than friction." Discuss this statement.

5. What do you understand by " coefficient of friction " between two plane surfaces?

A horizontal force of 2 lbs. acts on a body weighing 25 lbs. and just moves it slowly over a horizontal table. What is the value of the coefficient of friction?

How much work would be done in moving the 25-lb. weight over the table through a distance of 2 ft.?

U.L.C.I.

6. Design the outline of a heart cam to give a uniform rise and fall of 2 in. to a slider in contact with it. The diameter of the roller on the end of the slider is $\frac{1}{2}$ in., and the least distance between the centres of the roller and camshaft is 1·5 in.

7. Design the outline of a cam to move a slider vertically through 3 in. at uniform speed and also to return uniformly but at half the speed of the rise. Diameter of roller=$\frac{1}{2}$ in., and the least distance between the centres of the roller and camshaft=2·5 in.

8. In examples 6 and 7 plot graphs showing slider displacement (vertical) and time of one complete revolution of the camshaft (horizontal), assuming the camshaft to rotate at 60 revs. per min.

9. Explain how you would carry out an experiment on a screw-jack in order to determine the velocity ratio, mechanical advantage, and the efficiency of the jack. Indicate the type of result you would expect.

10. Define the terms " velocity ratio " and " force ratio." Under what conditions may these two quantities be equal?

In a machine used for lifting weights the velocity ratio is 5, and an effort of 20 lbs. is required to lift a load of 70 lbs. Determine the mechanical advantage, effect of friction, and the efficiency of the machine at this load.

11. What do you understand by the term " mechanical advantage "? A bucket filled with clay weighs 30 lbs. and is raised from a well by means of a wheel and axle. The

radius of the wheel is 15 in., and in seven revolutions the bucket rises through a distance of 5 ft. 6 in. What will be the least effort required ?

12. Define the terms " velocity ratio," " mechanical advantage," and " efficiency " as applied tc a machine, and state what relationship exists between these three terms.

In a certain lifting machine an effort of 3 lbs. will just lift a load of 30 lbs. If at this load the efficiency of the machine is 50 per cent., calculate the velocity ratio.

13. It is found by trial that to raise weights of 14, 28, 42, and 56 lbs. by means of a lifting appliance, efforts of 4·75, 7·5, 10·75, and 13 lb. weights are required. The velocity ratio of the tackle is 16. From these results determine :

(*a*) The law connecting the actual effort E with the load W ; and

(*b*) The effort, mechanical advantage, and the efficiency when a weight of 34 lbs. is being raised. U.L.C.I.

14. In a screw-jack the pitch of the screw is $\frac{1}{2}$ in., and the effort is applied at the end of a bar, the distance of whose extremity from the centre line of the jack is 2 ft. 4 in. Determine the velocity ratio of the jack. If the efficiency of the jack is 45 per cent., find what effort would be required to lift a load of 5 cwt.

How much effort is wasted in overcoming friction ?

15. The following values of effort E and load W were obtained on a rope pulley tackle, the velocity ratio of which was 4 :—

E lbs. .	2	3·9	5·8	10·2	14·6	19	23·4	27·8
W lbs. .	4	10	16	30	44	58	72	86

Plot graphs showing the relation between (*a*) load and effort, (*b*) load and friction, (*c*) load and mechanical advantage, (*d*) load and efficiency.

CHAPTER VII

ELEMENTARY PROPERTIES OF ENGINEERING MATERIALS

In all branches of engineering a knowledge of the properties of the materials used is of the utmost importance, but as our treatment of the subject in this work is only an introduction, the student who has a working knowledge of the mathematics required should continue his studies by reading standard works.

The smallest particle of any substance that can have a separate existence is called a molecule, and all bodies, solids, liquids, or gases are composed of a large number of these molecules. The molecules composing a substance are held together by what we call the force of *cohesion*, and in the case of solids this force is so great that it requires the application of a large force in order to separate them. In the case of liquids this force of cohesion is not so great, and in gases it is so slight that any gas will completely fill any vessel in which it is contained.

Metals used by the engineer should be *homogeneous*, *i.e.*, the composition of the metal should be uniform throughout, and it is the work of the metallurgist to see that this is the case. In the study of elasticity we assume that a material is *isotropic*, which means that the properties of the material are the same in all directions, but in practice this assumption is only approximate. Materials such as wood are not isotropic because it is a matter of everyday experience that such substances are decidedly very tough and strong when cut in a direction parallel to the grain, but they may be very brittle when cut across the grain.

Engineering materials have to be specified as to certain properties, such as strength, elasticity, hardness, ductility, and brittleness, but before discussing these properties the student should perform the following experiments, EXPERIMENT 14. *To Investigate the Straining Action of Forces on Materials.*—(*a*) Stretching a rubber cord. Fig. 78 shows the arrangement for this experiment.

A rubber cord C about 1 ft. long supports a scale pan P at one end, the other end being fixed to a support S, which is clamped on to the edge of a table. Take two points on the cord, say A and B, and when there is no load on the scale pan measure carefully the distance between A and B, which we will call the initial length of the piece of rubber.

Place a small weight on the pan and again measure the distance between A and B. This new distance minus the initial length will give the extension of the rubber for the given load. Repeat the experiment up to a definite maximum load, and in each case measure the extension.

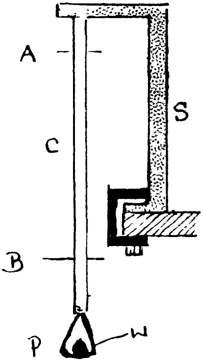


FIG. 78.

The following table shows the results of such an experiment, the load increasing 0·3 lb. up to a maximum of 1·5 lbs., the loads then being removed at the same rate. The second column shows the distance between A and B for each load. Complete the table, then plot a graph showing load (vertically) and extension (horizontally), and state conclusions.

Load on Scale Pan.	Distance between A and B.	Extension =Final Length—Initial Length.
Lbs.	In.	
0·0	10·7	...
0·3	11·4	...
0·6	12·3	...
0·9	13·2	...
1·2	14·2	...
1·5	15·6	...
1·2	14·7	...
0·9	13·7	...
0·6	12·8	...
0·3	11·9	...
0·0	11·1	...

(*b*) Deflection of a beam when supporting a load. Support a wooden lath, as shown in Fig. 79. Measure the height of the centre of the lath above the ground. Place weights on the lath, and after each load measure the height above the ground. The initial height minus the final height will give the deflection for each load. Plot a graph connecting load and deflection, and state conclusions.

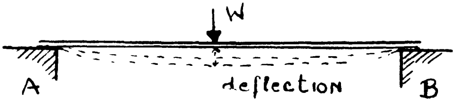


Fig. 79.

(*c*) Twist on a rod. Fig. 80 shows the arrangement for this experiment. The rod is clamped at B to a support, and A represents a pointer which is fixed to the rod and which moves over a scale S as a load W is applied to a string which passes round the circumference of the pulley, as shown. Carry out an experiment with such an arrangement and plot a graph showing the relation between load and angle of twist.

State conclusions.

Repeat Experiment 14 (*a*), (*b*), and (*c*), first taking the maximum load less than that previously taken, and, second, taking the maximum load greater than that previously taken.

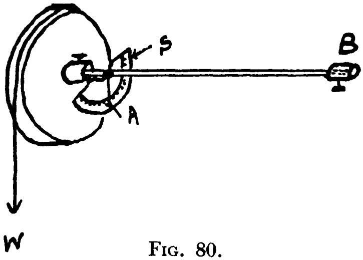


Fig. 80.

State conclusions.

If possible repeat these experiments, using different materials.

General Characteristics of a Load Deformation Graph

When a test is carried out on a material until the specimen fractures and we plot corresponding values of load and deformation, we obtain a graph similar to that shown in Fig. 81.

It will be noticed that the graph is a straight line up to the point marked A, which point is called the *elastic limit,* *i.e.*, within the elastic limit the deformation is proportional to the load.

Just beyond the elastic limit we come to the point marked B, which is known as the yield point. After this point has been reached we experience a greater deformation for the same increase in load. Eventually we reach the point C, which is the maximum load, and finally, at D, the specimen fractures.

As already stated, within the elastic limit we obtain a straight line graph OA as the load is gradually increased, and if we then decrease the load at the same rate we shall travel back along the line AO, *i.e.*, after the test the material will return to its initial dimensions, or, in other words, the material is said to be *elastic*.

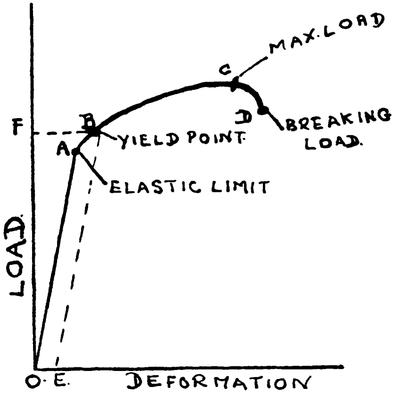


FIG. 81.

On the other hand, if we had continued to load the specimen beyond the elastic limit, say to some point such as F, and we then started to unload, we should travel back along the dotted line shown in Fig. 81, and when finally we removed the last load the material would be deformed by an amount represented by OE, and this deformation which remains is known as the *permanent set*. It should be noted that if the permanent set is not too great and if the material is not used for some time, it may gradually return to its original condition, but generally between the points B and D the material is said to be *plastic*, *i.e.*, any deformation is more or less permanent.

STRESS AND STRAIN

Fig. 82 represents a rod PQ supported at P and hanging vertically, a load W lbs. being hung on the end at Q. Suppose L in. is the initial length of the rod, A sq. in. is the sectional area of the end, and the load W lbs. causes an extension e in.

We define the term stress as the ratio $\frac{\text{load}}{\text{area}}$, and the strain is given by the ratio $\frac{\text{increase in length}}{\text{original length}}$. Since the load is given in pounds and the area in square inches, the unit of stress will be pounds per square inch. The unit of strain will simply be a number, as both the original length and the extension are measured in the same units.

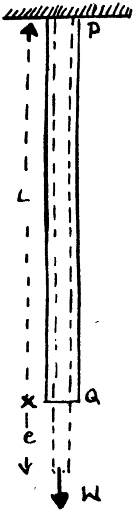


FIG. 82.

We have already seen that within the elastic limit the deformation is proportional to the load, and this relationship is known as Hooke's Law. The law has been modified by Young, who stated that within the elastic limit the stress is proportional to the strain. This being the case the ratio $\frac{\text{stress}}{\text{strain}}$ is a constant quantity, and this ratio is denoted by E, and is called Young's Modulus of Elasticity.

In the above case, stress$=\frac{W}{A}$ and strain$=\frac{e}{L}$, therefore we can write $E=\frac{W}{A}\Big/\frac{e}{L}$, or $E=\frac{W}{A}\cdot\frac{L}{e}$, from which we can determine any one quantity if the remaining quantities are known. (Note that the unit of Young's modulus is the same as the unit of stress.)

Example 1.—A steel wire 0·1 in. in diameter is 20 ft. long, and supports a load of 100 lbs. Determine (*a*) the stress, (*b*) the extension in inches.

Young's modulus of elasticity=30,000,000 lbs. per sq. in.

$$(a)\quad \text{Stress}=\frac{\text{load}}{\text{area}}=\frac{100\text{ lbs.}}{0{\cdot}7854\times 0{\cdot}1^2\text{ sq. in.}}$$

$$=\frac{100}{0{\cdot}007854}=12710\text{ lbs. per sq. in.}$$

$$(b)\qquad \text{Young's modulus}=\frac{\text{stress}}{\text{strain}},$$

i.e., $30000000=\frac{12710\times240}{e}$ where e is the extension inches,

i.e., $e=\frac{12710\times240}{30000000}=0{\cdot}1016$ in.

The load necessary to fracture a specimen divided by the original area of the section gives us what is termed the ultimate strength of the material, or, if the stress is tensile, it may be called the tenacity. The greatest calculated stress to which the material may be subjected is termed the working stress, and the ratio $\frac{\text{ultimate strength}}{\text{working stress}}$ has a very important bearing on all engineering problems and is known as the *factor of safety*. In dealing with factors of safety we have to make allowance for imperfections in the material, mistakes made by the workmen, neglect and carelessness, accidental overloading of the machine or structure, and deterioration due to time.

Example 2.—A steel column of circular section is required to carry a load of 60 tons. Calculate the diameter of the column, assuming the ultimate strength of steel to be 30 tons per sq. in. Allow a factor of safety of 5.

Factor of safety $=\frac{\text{ultimate strength}}{\text{working stress}}$, *i.e.*, $5=\frac{30\text{ tons per sq. in.}}{\text{working stress}}$, from which working stress $=6$ tons per sq. in.

But stress $=\frac{\text{load}}{\text{area}}$, *i.e.*, $6=\frac{60}{\text{area}}$, or sectional area $=10$ sq. in., *i.e.*, $0{\cdot}7854d^2=10$ where $d=$ the required diameter. From this

$$d=\sqrt{\frac{10}{0{\cdot}7854}}=3{\cdot}568 \text{ in., say, } 3{\cdot}6 \text{ in.}$$

In the course of his daily work the student should examine parts of a machine or structure and note what forces may be acting on it and whether the resulting stress is tensile, compressive, shear, torsion, or bending, the latter being a combination of tensile, shear, and compressive stresses.

In carrying out a test on a specimen bar of metal the following points should receive attention :—

First of all, there should be a good choice of specimens, and the length of a specimen should be several times its diameter. Sharp changes of section should be avoided because a metal will easily fracture at a sharp corner, and especially if the specimen is brittle. For the same reason the metal should be free from notches or ruts. Avoid any treatment which is likely to alter the properties of the metal, and when the load is applied it should be applied gradually and centrally, otherwise there will not be a uniform distribution of the load.

A part of a machine or structure will always be designed so as to carry a load greater than that which will usually come on to it, but the elastic limit must not be reached, and in the case of repeated loading, when a structure may become "fatigued," the stresses must be well below the elastic limit.

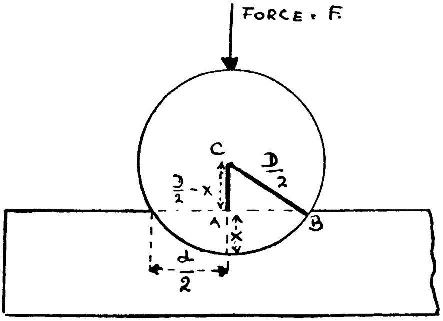


FIG. 83.

The strength of a material is defined as the load per unit area the material will stand without fracture, and the next property we have to discuss is *hardness*, which is independent of the strength.

In dealing with hardness it is usual to apply what is known as the Brinell test. In this test a specimen is indented by pressure applied to a specially hardened steel sphere, and what is known as the hardness number is the ratio $\frac{\text{force applied}}{\text{area of indentation}}$. Usually the force applied varies from 2,000 to 3,000 kg., and the diameter of the sphere is 1 cm.

Consider Fig. 83. C is the centre of a steel sphere of diameter D, and a force F presses this sphere into the metal causing an indentation x, the diameter of this indentation being d. In order to determine the area of the indentation we must know the depth x. To calculate x consider the right-angled triangle BAC. Here $BC^2=AB^2+AC^2$, or, substituting the known quantities, $\left(\frac{D}{2}\right)^2=\left(\frac{d}{2}\right)^2+\left(\frac{D}{2}-x\right)^2$. This may be written as

$$\left(\frac{D}{2}\right)^2=\left(\frac{d}{2}\right)^2+\frac{D^2}{4}-\frac{2Dx}{2}+x^2, \text{ or } x^2-Dx+\frac{d^2}{4}=O.$$

Solving this quadratic we find $x=\frac{D\pm\sqrt{D^2-d^2}}{2}$.

Area of indentation $=\pi Dx=\frac{\pi D}{2}(D\pm\sqrt{D^2-d^2})$, so that the

$$\text{Brinell hardness number}=\frac{F}{\frac{\pi D}{2}(D\pm\sqrt{D^2-d^2})}.$$

In using this formula in a numerical case the + sign in front of the square root will obviously give a wrong value for the area, and must therefore be neglected.

Example 3.—Determine the Brinell hardness number for a sample of boiler plate, given that a force of 2,000 kg. applied to a sphere 10 mm. diameter caused an indentation of diameter 4·25 mm.

Substituting the given values in the above formula for x, we have

$$x=\frac{10-\sqrt{100-18{\cdot}06}}{2}=\frac{10-9{\cdot}05}{2}=0{\cdot}475.$$

$$\text{Area}=\pi Dx=3{\cdot}142\times10\times0{\cdot}475=14{\cdot}92.$$

$$\text{Therefore Brinell hardness number}=\frac{2000}{14{\cdot}92}=134.$$

Certain metals can be drawn out in the form of a thin wire and such metals are said to be *ductile*. This property depends to a great extent on the strength of the material, and it decreases with an increase in temperature. If a material does not change its shape under the action of a force but simply breaks up, the material is said to be *brittle*, and very frequently during the operation of wire-drawing the material will become so brittle that it breaks under the action of the pulling force. In such cases the metal has to be annealed, *i.e.*, it is heated to a red heat and allowed to cool slowly.

If a metal can be hammered out in the form of a very thin sheet, it is said to be *malleable,* and this property increases slightly with increase of temperature. If a metal is not malleable, it is said to be *short.*

All the above-mentioned properties of a metal will, of course, depend on the chemical and physical treatment to which it has been subjected, and a slight addition or subtraction of certain chemical compounds will entirely alter its nature. Heat will cause an elastic metal to become plastic, and lead, which is a non-elastic material, can under the influence of a great pressure be made to flow like water. In the making of coins the metal disc is placed between steel dies, and when under pressure the metal flows and fills completely all impressions on the die.

Before concluding this chapter, which, as already stated, is the introduction to a very important section of the student's work, we might consider briefly one or two very common materials which the engineer uses.

In certain areas in Great Britain, America, and on the continent of Europe minerals are to be found which contain iron, which after suitable treatment is turned out as cast iron, wrought iron, or steel.

The minerals which contain iron are heated to a very high temperature in what is known as a blast furnace, and mixed with the mineral is a quantity of lime, the object of which is to assist chemical reactions. In time the metal is separated and collected in liquid form at the bottom of the furnace. It is then run off and cast into bars called "pigs," which can be used as cast iron or converted into wrought iron or steel.

Cast iron varies greatly in quality, depending on the nature of the ore from which it has been taken, but generally it is a grey metal which when broken shows a crystalline structure. It contains from 3 to 4 per cent. carbon, and has a high melting-point. It is important always to allow a casting to cool uniformly, otherwise stresses may be set up in parts of the metal which may render it useless for certain classes of work. The metal is very brittle, and should not be used in machines or structures which have to withstand severe shocks.

Wrought iron is obtained from cast iron by removing the carbon. It is a softer material than cast iron, and being much more pliable will easily bend without fracture. It is repeatedly rolled into bars, and this operation makes it very tough and fibrous, and at a suitably high temperature can be welded.

Steel is iron containing, roughly, ½ per cent. carbon. It is considerably stronger and more ductile than wrought iron, and has a greater coefficient of expansion than cast iron.

There is one disadvantage in connection with the use of iron or steel, and that is because when exposed to moist air it forms red oxide, or rust, and this, as you know, will cause *the metal to deteriorate rapidly. This difficulty can be over*come to some extent by applying a lacquer, such as a solution of wax in benzine. The solution should be applied with a fine brush, and when the wax solidifies out of the solution it can easily be wiped off, just a sufficient amount being left to prevent rust from forming.

Copper when obtained in a pure form is a very soft and ductile material and is a very good conductor of heat and electricity.

Bronze is a metal containing a mixture of about 80 per cent. copper with tin, zinc, manganese, and phosphorus. The metal is strong, and since it does not corrode is a suitable material for pumping apparatus and ship propeller blades.

Brass consists of two parts copper to one of zinc. It is not a very strong material, but it is easy to work, gives a polished surface, and does not corrode.

White metal is a mixture of tin, copper, and antimony. It is a soft material, takes a smooth surface, and, like brass, is suitable for linings and to reduce friction between moving surfaces.

The properties of a piece of timber will, of course, depend on the tree from which it has been obtained. Soft woods are obtained from resinous trees, non-resinous trees providing us with the hard woods. Again the properties will depend on the part of the tree from which it has been cut and the way in which it has been cut, tensile and compressive strengths being much greater when a piece of wood is cut along the grain. Finally, the strength of a piece of wood will be its maximum when it contains about 5 per cent. of its own weight of water.

SIXTH SET OF EXAMPLES

1. Describe an experiment by means of which you would determine the relation between the load and the extension in a wire as it is gradually loaded up to its breaking point.

Sketch roughly the type of load-extension graph you would expect. A wire is 20 ft. long and 0·2 in. diameter, and when supporting a load of 5 lbs. it stretches 0·15 in. Calculate the stress and strain.

2. Calculate the diameter of a wrought-iron bar which will safely withstand a direct pull of 13 tons, the working stress of wrought iron being 9,000 lbs per sq. in.

3. What do you understand by "elastic limit"? Describe simple experiments to illustrate your answer, and explain the significance of the elastic limit in engineering practice.
U.L.C.I.

4. Define the following terms: "Dead load," "live load," "factor of safety," "fatigue of materials."

In the basement of a mill there are fifty-two cast-iron pillars supporting the superstructure. Each of these pillars is 10 in. outside diameter, and the metal is $1\frac{1}{2}$ in. thick. Assuming these pillars are subject to a simple compressive stress, what total load in tons can they support, allowing a factor of safety of 8?

NOTE.—The ultimate breaking load of cast iron when in compression is 40 tons per sq. in. U.L.C.I.

5. What do you understand by the terms "stress," "strain," and "modulus of elasticity"? A tie-rod 100 ft. long and 2 sq. in. sectional area is stretched $\frac{3}{4}$ in. under a tension of 32,000 lbs. What is the intensity of the stress, the strain, and the modulus of elasticity? U.L.C.I.

6. Explain the importance of the term "factor of safety" when dealing with engineering problems.

7. Mention various ways in which materials may be deformed by the action of forces, and give examples from engineering practice.

A steel wire 20 ft. long and 0·1 in. diameter carries a tensile load of 75 lbs. Calculate the tensile stress and the elongation under this load.

$$E = 30000000 \text{ lbs. per sq. in.}$$

8. A mild-steel bar of square section is required to carry a load of 20 tons. Calculate the size of the bar if the ultimate strength of mild steel is 30 tons per sq. in. Allow a factor of safety of 6.

9. Determine the Brinell hardness number of a piece of mild steel given that the force applied to a sphere 1 cm. diameter was 2,000 kg., and that the diameter of the indentation was 0·45 cm.

10. In testing for the hardness of a piece of rail steel a pressure of 2,000 kg. was applied to a steel sphere 1 cm. diameter, and caused an indentation in the metal of diameter 0·371 cm. Determine the Brinell hardness number.

11. Define the terms "stress" and "strain."

A round steel tie-rod is required to support a load of 12 tons. If the maximum stress allowed in the material is 7 tons per sq. in., calculate the required diameter of the rod.

12. Explain the meaning of the term "factor of safety."

A tie-rod supports a load of 6 tons. Calculate the diameter of the rod if the tensile stress in the materials is 26 tons per sq. in. Allow a factor of safety of 6.

13. State what factors have to be taken into account when dealing with factors of safety.

A steel tie-rod is 4 in. broad and 1 in. thick and supports a load of 20 tons. If the ultimate tensile stress of the material is 30 tons per sq. in., what is the factor of safety?

14. A steel wire 0·08 in. diameter and 50 ft. long is subjected to tension by a load of 112 lbs. Determine (*a*) the stress in pounds per square inch, (*b*) the strain, and (*c*) the elongation in inches. U.L.C.I.

CHAPTER VIII

MECHANICS OF FLUIDS

THE reader is now familiar with the fact that a solid body always offers a resistance to any change of shape when a force acts upon it, and that in many cases the force applied must be very great in order to overcome the force of cohesion which holds the molecules of a body together.

In the case of fluids, with which we now have to deal, the force of cohesion is so slight that practically no resistance is offered to change of shape, and the fluid will ultimately take the shape of any vessel in which it is contained. Fluids may be subdivided into liquids and gases, but in this chapter we shall confine our attention to liquids, two important properties of which are that they always have a free surface, and their volumes are, for all practical purposes, independent of the pressure applied. When we speak of the pressure at a point in a liquid we mean the force acting per unit area, and the pressure acting at any point in a liquid at rest is always perpendicular to any surface with which it may be in contact, whether that surface be a solid or an adjacent portion of the fluid.

We now have to consider one or two conditions of equilibrium of liquids and of solids immersed in liquids.

Theorem 1.—To prove that the pressure of a liquid at rest is the same at all points in the same horizontal plane.

Fig. 84 represents a small horizontal cylinder of a liquid contained in a tank. The points A and B are the two ends of this cylinder, and we will assume that the sectional area of the ends is *a*. The cylinder is in equilibrium under the action of a number of forces. There will be the liquid pressure on the curved surfaces and the weight of the cylinder acting in a direction perpendicular to the axis, and according to our rules of equilibrium these forces balance one another. There will also be fluid pressures acting on the ends of the cylinder in the direction of the axis. Again, since there is no motion in the direction of the axis, the force on the end A must equal the force on the end B. Suppose P to be the pressure on the end A, then the force acting at A will be Pa, and if p is the pressure at B, then the force acting at B will be pa, so that $Pa=pa$, or $P=p$, *i.e.*, the pressure is the same at all points in the same horizontal plane.

Theorem 2.—To prove that the pressure at any point in a liquid at rest is directly proportional to the depth of the point below the surface of the liquid.

Consider a vertical cylinder AB of a liquid contained in a tank, A being a point in the surface of the liquid, and B being a point at a depth d (Fig. 85). Let a=sectional area of this cylinder at B.

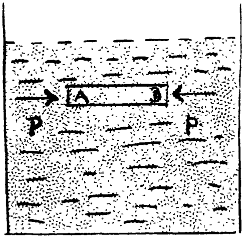


FIG. 84.

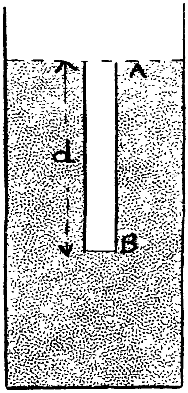


FIG. 85.

This cylinder of liquid will be in equilibrium under a number of forces. These will be the pressures on the curved surface acting horizontally, and by Theorem 1 these balance one another. There will also be a force acting vertically upwards at B, and the weight of the cylinder acting vertically downwards. Let P=pressure on the base B, then the force acting upwards at B will be Pa. If w=weight per unit volume of the cylinder, then the total weight of the cylinder will be wda, so that $Pa=wda$, or $P=wd$, *i.e.*, the pressure is directly proportional to the depth.

NOTE.—If p=atmospheric pressure, we have

$$Pa = wda + pa, \text{ or } P = wd + p.$$

Theorem 3.—To prove that the surface of a liquid at rest is horizontal.

Suppose A and B (Fig. 86) to be two points in the surface of a liquid at different levels, and let P=atmospheric pressure. Draw AC vertical and BC horizontal, then the pressure at C will be $P + w\text{AC}$ by Theorem 2, where w=weight per unit volume of the liquid. But the pressure at A=pressure at B=P, therefore AC=O, *i.e.*, the surface of a liquid at rest is horizontal.

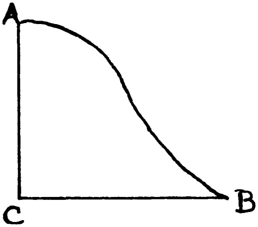


FIG. 86.

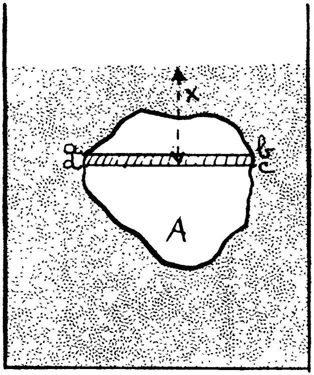


FIG. 87.

Theorem 4.—To prove that the total force acting on a plane area immersed in a liquid is given by the product area of surface × depth of the centre of area × weight per unit volume of the liquid.

In Fig. 87 A represents a plane area immersed in a liquid, the weight per unit volume of which is w.

Divide the area into a number of narrow strips, such as *abcd*, these strips being parallel to the surface of the liquid. The strips are assumed to be very narrow, so that the pressure will be the same throughout each, and the depth of each below the surface of the liquid we will call x_1, x_2, x_3, etc. The forces acting on these strips will be wx_1a_1, wx_2a_2, wx_3a_3, etc., where a_1, a_2, a_3 . . . represent the areas. We can therefore state that the total force acting on the whole area will be given by

$$wx_1a_1+wx_2a_2+wx_3a_3+ \ . \ . \ . =w(x_1a_1+x_2a_2+x_3a_3+ \ . \ . \ .).$$

If $\bar{x}$=the depth of the centre of area of the total area A we have, by taking moments about the surface of the liquid, $A\bar{x}=x_1a_1+x_2a_2+x_3a_3+ \ . \ . \ .$, and substituting this in the above equation for the total force acting on the area, we get total force$=wA\bar{x}$, *i.e.*, the total or resultant force is equal to the product area×depth of centre of area×weight per unit volume of the liquid.

Example 1.—A rectangular tank is 10 ft. long by 4 ft. wide by 2 ft. deep, and is filled with water which weighs 62·5 lbs. per cub. ft. Find the resultant force acting on the shorter side of the tank.

Area of side of tank$=4\times2=8$ sq. ft., and the depth of the centre of area of this side is 1 ft., therefore required resultant force$=8\times1\times62{\cdot}5=500$ lbs.

Centre of Pressure

Any plane area which is immersed in a liquid will experience a thrust which is given by the product pressure at the centre of gravity×area of plane. A resultant force will be necessary in order to balance this thrust, and the point in the area through which this resultant force acts is called the centre of pressure.

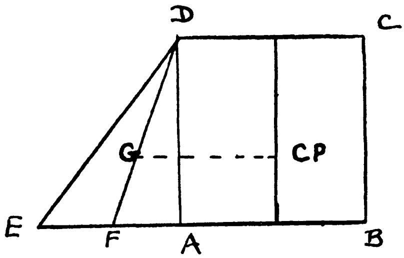


Fig. 88.

In Fig. 88 ABCD represents the face of a rectangular tank of side 1 ft. If the tank is filled with water it will contain 1 cub. ft., the weight of which is 62·5 lbs.

From A mark off a distance AE to represent 62·5 lbs. and join ED, then the triangle ADE may be used to obtain the pressure at any depth in the tank, since the pressure at the surface is, of course, zero. The centre of gravity of the triangle ADE will determine the position of the centre of pressure for the face of the tank ABCD.

The student who has performed Experiment 6, Chapter IV., will remember that the centre of gravity of a triangular area is $\frac{1}{3}$ the height of the triangle measured from the base, *i.e.*, the centre of gravity of the triangle ADE is along the median DF at the point G, which is $\frac{1}{3}$AD. Draw a vertical line through the point half-way between A and B, and let the horizontal through G cut this vertical line at CP, which is the required centre of pressure for the surface ABCD, *i.e.*, the centre of pressure is $\frac{2}{3}$ the depth of the liquid measured from the surface.

The determination of centres of pressure for areas of different shapes is beyond our present scope, but the following figures may be given for reference :—

Rectangle or parallelogram with one side in the surface of the liquid centre of pressure$=\frac{2}{3}$ vertical depth.

Triangular area with one side in the surface, centre of pressure is half-way down the median of the triangle. If, however, the vertex of the triangle is in the surface of the liquid and the base is parallel to the surface, then the centre of pressure is $\frac{3}{4}$ the length of the median.

A circular disc diameter d with the circumference touching the surface of the liquid centre of pressure$=\frac{5}{8}d$.

Example 2.—The dimensions of a vertical rectangular sluice gate are 5 ft. by 4 ft., and it is submerged 1 ft. below the surface of the water with its longer side parallel to the surface. Determine the position of the centre of pressure (1 cub. ft. of water weighs 62·5 lbs.).

In Fig. 89 ABCD represents the gate with the side DC 1 ft. below the surface of the water FE.

Total force on the gate will be given by the product area×depth of centre of gravity×weight per unit volume of water$=20\times3\times62{\cdot}5=3750$ lbs.

Total force on area represented by DCEF$=5\times\frac{1}{2}\times62{\cdot}5$ $=156{\cdot}25$ lbs. The pressure on this area will act at a distance of $\frac{2}{3}$ ft. from the surface. The total force acting on the whole area ABEF will be the sum of the above two forces, *i.e.*, $3750+156{\cdot}25=3906{\cdot}25$ lbs., and this will act at a distance of $\frac{10}{3}$ ft. from the surface.

If d=the required depth of the centre of pressure of the gate, we have, by taking moments about the surface of the water,

$$3750d+156\cdot25\times\tfrac{2}{3}=3906\cdot25\times\tfrac{10}{3},$$

whence $$d=3\cdot18 \text{ ft. (nearly).}$$

EXPERIMENT 15. *Solids Immersed in Liquids.*—Obtain an ordinary balance and use it to determine the mass in grammes of a solid A of which the volume in cubic centimetres is either known or can be determined. Arrange a small bridge on which is placed a vessel containing water, as shown in Fig. 90, and determine the mass of the solid A when it is suspended in the water. Its mass or weight will appear to be less than in the previous case, and if you perform the experiment carefully you will find that the number which expresses in grammes the difference between the real and apparent weights of the solid will be equal to the volume of the solid in cubic centimetres.

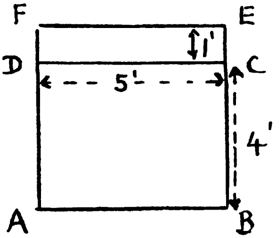


FIG. 89.

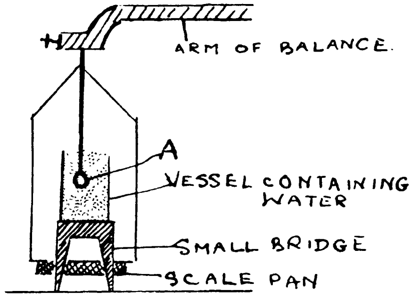


FIG. 90.

The above experiment verifies what is known as the Principle of Archimedes, which states that the upward pressure of a liquid on a solid immersed in it is equal to the weight of liquid displaced.

CONDITIONS FOR EQUILIBRIUM OF A BODY FLOATING IN A LIQUID

In order that a body may be in equilibrium when floating in a liquid, two conditions must be satisfied, viz., the weight of liquid displaced must be equal to the weight of the body and the centre of gravity of the liquid displaced (called the centre of buoyancy) must be in the same vertical line as the centre of gravity of the floating body. These two conditions only are necessary for equilibrium, which may be either stable, unstable, or neutral. For stability, which has to be dealt with in the design of a ship, a third condition must be satisfied.

Consider Fig. 91, in which A, B, and C represent the section of a ship through the centre of gravity in a plane at right angles to the length of the ship.

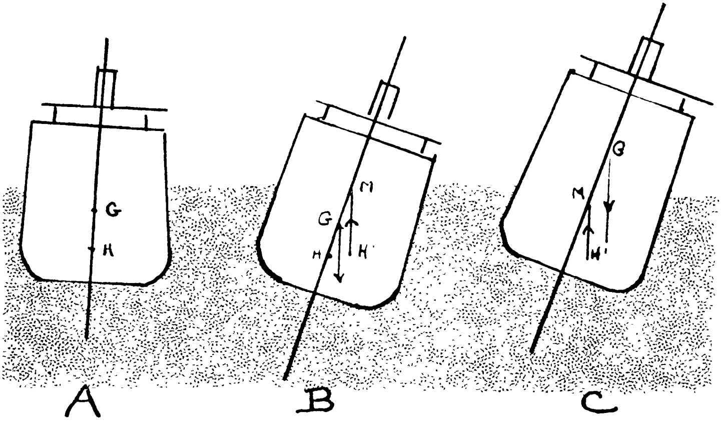


Fig. 91.

In the first case (A, Fig. 91) the ship is at rest, G is the centre of gravity and H is the centre of buoyancy. The weight of the ship acts vertically downwards through G, and the thrust due to the water acts vertically upwards through H, *i.e.*, G and H are in the same vertical line. If the ship turns through an angle, as shown at B (Fig. 91), then the centre of buoyancy will be in a different position, such as, say, H′. The weight of the ship will still be vertically downwards through G, and the thrust due to the water will act vertically upwards through H′, and it will be noticed that the vertical line through H′ cuts HG produced in some point M, which is called the *metacentre.*

In B (Fig. 91) the metacentre is above the centre of gravity of the ship, but in C (Fig. 91) the point M falls below G. The weight of the ship and the thrust due to the water form a couple, the direction being anticlockwise in B and clockwise in C, *i.e.*, in case B the ship will return to its original position. We can now state the third condition for stable equilibrium mentioned above, which is that the metacentre must be above the centre of gravity of the floating body.

DENSITY AND SPECIFIC GRAVITY

The density of a substance is defined simply as the ratio $\frac{\text{mass}}{\text{volume}}$, the units being grammes per cubic centimetre, pounds per cubic inch, etc. We define the specific gravity of a substance as the weight of a given volume of the substance compared with the weight of an equal volume of water. When we say that the specific gravity of copper is 8·9, we mean that, bulk for bulk, the copper will weigh 8·9 times as much as water. Suppose the weight of unit volume of water $=w$, then the weight of V units of volume will be Vw, and the weight of any substance which is S times as heavy as water will be given by the relation $W=VwS$, from which we can find any one quantity if the others are known.

Example 3.—Determine the volume occupied by 100 lbs. of lead given that the specific gravity of lead is 11·4 and the density of water is 62·5 lbs. per cub. ft.

Using the above formula for specific gravity, we have

$$100 \text{ lbs.} = V \times 62{\cdot}5 \text{ lbs. per cub. ft.} \times 11{\cdot}4,$$

$$\textit{i.e.,}\quad V = \frac{100 \text{ lbs.}}{62{\cdot}5 \text{ lbs. per cub. ft.} \times 11{\cdot}4} = 0{\cdot}1404 \text{ cub. ft.}$$

Theorem 5.—To prove that when a solid floats in a liquid the ratio

$$\frac{\text{Volume of the solid}}{\text{Volume of part immersed}} = \text{ratio } \frac{\text{specific gravity of liquid}}{\text{specific gravity of solid}}.$$

Fig. 92 represents a solid A floating in a liquid B. Let V represent the volume of the solid and V' represent the volume below the surface of the liquid. Also let S be the specific gravity of the solid, and S' be that of the liquid, then, since the weight of a body which floats in a liquid=weight of the liquid displaced, we can write VS=V′S′, or $\frac{V}{V'}=\frac{S'}{S}$.

To find the tension in a string which supports a body at a fixed depth below the surface of a liquid.

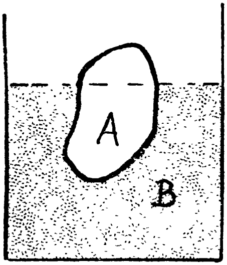


FIG. 92.

The student will realise that the tension in the string will act either upwards or downwards, depending on whether the weight of the body to be held in position is greater or less than the weight of liquid displaced. In Fig. 93 (*a*) represents the former case and (*b*) the latter. In both cases the weight of the body will act vertically downwards, and the thrust due to the liquid or the buoyancy will act vertically upwards.

If W=weight of the body, B=buoyancy, and T=tension in the string, in case (*a*) we have T+B=W, and in case (*b*) we have T+W=B.

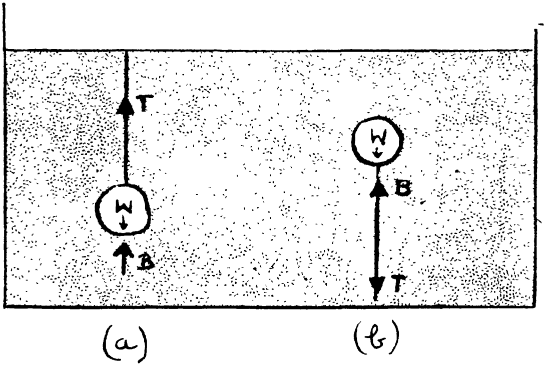


FIG. 93.

If S=specific gravity of the solid, the weight of an equal volume of the liquid or the buoyancy will be $\frac{W}{S}$ from the definition of specific gravity, so that in case (*a*) the tension in the string will be given by the relation $T=W-\frac{W}{S}$, and in case (*b*) it will be given by the relation $T=\frac{W}{S}-W$.

Example 4.—A sphere of lead (specific gravity 11·5) weighs 46 lbs. and is suspended in water by means of a wire rope. What is the tension in the rope?

Weight of lead in air=46 lbs., and weight of an equal volume of water or buoyancy due to the water$=\frac{46}{11 \cdot 5}=4$ lbs. Therefore tension in the rope=46−4=42 lbs.

Theorem 6.—Given the volumes and specific gravities of a number of substances to determine the specific gravity of the mixture.

Let V_1, V_2, V_3 . . . represent the volumes of a number of substances whose specific gravities are respectively S_1, S_2, S_3. . . . The total weight of the mixture will then be $(V_1S_1+V_2S_2+V_3S_3+ \dots)w$, where w=weight per unit volume of water. The total volume of the mixture will be $V_1+V_2+V_3+ \dots$, and if S=the required specific gravity of the mixture, we have

$$S(V_1+V_2+V_3+ \dots)w=(V_1S_1+V_2S_2+V_3S_3+ \dots)w,$$

or

$$S=\frac{V_1S_1+V_2S_2+V_3S_3+ \dots}{V_1+V_2+V_3+ \dots},$$

i.e., the specific gravity of the mixture of a number of substances is given by the relation $\frac{\text{total weight of the substances}}{\text{volume of the mixture}}$.

EXPERIMENT 16. *To Find the Specific Gravity of a Piece of Iron.*—Obtain a piece of the metal and determine its weight in air and then determine its weight in water. The difference between these two values will give us the weight of an equal volume of water, so that knowing the weight of the piece of iron in air and the weight of an equal volume of water the specific gravity of iron may be determined. A piece of iron weighed 8·06 grm. in air and 7·05 grm. in water, what value do these readings give for the specific gravity of iron?

Determine the specific gravities of other solids by a similar method.

EXPERIMENT 17. *To Find the Specific Gravity of a Liquid.*—Obtain a piece of metal and find its weight in air, say, W_1 grm. Now weigh the metal in water, say, W_2 grm., so that weight of water displaced$=W_1-W_2$ grm.

Next weigh the piece of metal in the liquid of which the specific gravity is required, say, W_3 grm., *i.e.*, weight of liquid displaced$=W_1-W_3$ grm., therefore required specific gravity of the liquid$=\dfrac{W_1-W_3}{W_1-W_2}$.

The weight of the piece of iron used in Experiment 16 was 6·95 grm. when weighed in a salt solution. Determine the specific gravity of the solution.

Repeat the experiment to determine the specific gravities of other common liquids.

EXPERIMENT 18. *To Find the Specific Gravity of a Substance which Floats in Water.*—Attach a weight, known as a sinker, to the substance by means of a thread. Weigh the two together, the sinker being in water and the substance in air, say, W_1 grm. Now weigh the sinker and the substance together in water, say, W_2 grm. Weight of water displaced by substance$=W_1-W_2$ grm. Weight of sinker alone in water$=W$ grm., therefore weight of substance in air$=W_1-W$ grm., so that the required specific gravity of the substance $S=\dfrac{W_1-W}{W_1-W_2}$.

What is the specific gravity of wax from the following readings :—

Weight of sinker in water and wax in air =7·58 grm.
Weight of sinker and wax in water =6·95 ,,
Weight of sinker in water =7·05 ,,
Weight of wax in air =0·53 ,,

Repeat the experiment for other substances which float in water.

Example 5.—A small piece of metal weighs 12 grm. in air, 8 grm. in water, and 9 grm. in a certain liquid. Determine the specific gravity of the liquid.

The weight of a volume of water equal to the volume of the piece of metal will be given by the difference between the weight of the metal in air and in water, viz., 12−8=4 grm. Also the weight of an equal volume of the liquid will be 12−9=3 grm. Therefore specific gravity of liquid $=\frac{\text{weight of a certain volume of liquid}}{\text{weight of an equal volume of water}}=\frac{3}{4}$.

The specific gravities of solids in the form of small particles, such as, say, lead shot, and also of liquids may be determined by means of what is called a specific gravity bottle, as shown in Fig. 94, water and liquids being filled up to a certain mark A on the stem.

To find the specific gravity of lead shot by this method we first of all weigh the lead shot, say, W grm. Next fill the bottle with water up to the mark A and weigh it, say, W_1 grm., *i.e.*, $W+W_1$ is the weight of the bottle solid and water. Now place the lead shot in the bottle and remove the water until it again stands at the mark A. Weigh again, say, W_2 grm.

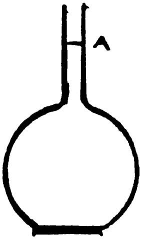


FIG. 94.

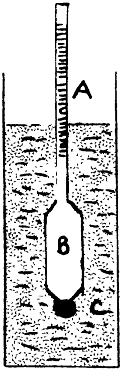


FIG. 95.

The weight of water displaced by the lead shot will be $W+W_1-W_2$, so that the required specific gravity S will be

$$\frac{W}{W+W_1-W_2}.$$

When the engineer requires the specific gravity of a liquid he uses a common hydrometer, which is shown in Fig. 95. It consists of three parts, A, B, and C. The bulb C contains mercury, so that it may float upright in a liquid, the bulb

B is filled with air, and the stem A contains a graduated scale. The instrument will displace its own weight of a liquid when floating in it, and the less dense the liquid the deeper the hydrometer will sink in it. The graduation mark to which the instrument sinks determines the specific gravity of the liquid.

WATER IN MOTION

EXPERIMENT 19.—Obtain a cylindrical glass vessel and fill it with water. Drop some fine sand or chalk into the beaker and stir the water by means of a rod. Notice how the sand is carried along by the motion of the water until it is finally heaped up at the bottom of the glass, as shown in Fig. 96.

The next time you happen to be in a flat part of the country where there is a winding river notice the opposite banks of the river at a bend. If you can take accurate readings, you will notice that the river is slightly higher on one side than the other. In many cases you will also notice that parts of the river bank are from time to time washed away on one side and a mud bank may be formed on the opposite bank, the state of affairs being illustrated in Experiment 19.

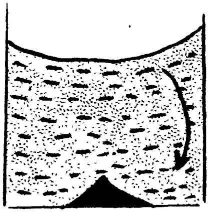


FIG. 96.

The shape of the water surface will show how the pressure varies at different points below it. The pressure is lowest at the centre of the vessel and rises towards the sides, and this difference in pressure between the two points causes a flow of water from the sides towards the centre. This flow is continued by the flow of surface water from the centre outwards, the sides of the vessel or the concave bank of a river in turn deflecting it downwards.

WATER DISCHARGED THROUGH A SHARP-EDGED ORIFICE

A quantity of water W lbs. at a height h ft. above some fixed level will possess Wh ft.-lbs. of potential energy, and this energy will be converted into kinetic energy if the water is allowed to fall through the height h.

Suppose we have an opening A sq. ft. near the bottom of a tank and that water flows through this opening with a speed V ft. per sec., then theoretically the quantity of water Q cub. ft. per sec. will be given by the product AV. Also, we know that the speed of a body falling through a height h is given by the relation $V=\sqrt{2gh}$, *i.e.*, $Q=A\sqrt{2gh}$.

In practice the quantity of water discharged per second through an orifice, as given by the above formula, is found to be too high, due to two facts which have been proved by experiment. First, the actual area of the jet which emerges has been found only 0·64 times that of the area of the orifice, and this number is known as the coefficient of contraction of the area. Second, owing to fluid friction, the speed of the jet as it emerges from an orifice has been reduced to 0·97 times the speed given by $\sqrt{2gh}$, and this number is known as the coefficient of velocity. The actual quantity of water flowing through an orifice per second takes into consideration these two coefficients, the product of which is denoted by a constant number K, which is called the coefficient of discharge. The formula for the quantity of water flowing through a sharp-edged orifice is therefore $Q=KA\sqrt{2gh}$.

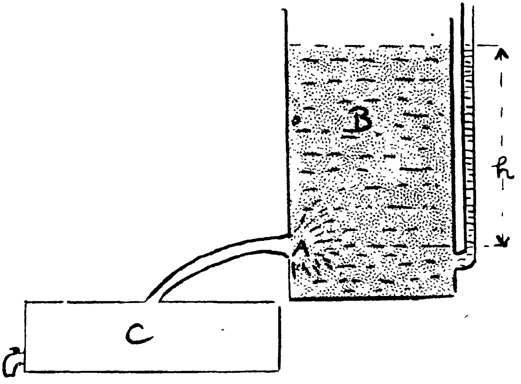


FIG. 97.

EXPERIMENT 20. *To Determine the Relation between the Head of Water Producing Discharge through Orifices and the*

Quantity of Water Discharged.—The apparatus is shown in Fig. 97. The head of water h in tank B is kept steady, the water being discharged through an orifice A into a tank C, from which it is collected and measured.

The following readings were obtained by a student with an apparatus similar to that shown in Fig. 97 :—

ORIFICE, SQUARE, ½ IN. SIDE

Duration of Test, T Secs.	Head of Water, H Ft.	Weight Discharged in T Secs.	Weight Discharged per Second, W Lbs.
		Lbs.	
15	0·5	6·0	...
10	1·0	6·0	...
10	1·5	6·5	...
10	2·0	8·0	...
5	2·5	5·0	...
ORIFICE, CIRCULAR, ½ IN. DIAMETER			
10	2·5	6·0	...
10	2·0	5·5	...
10	1·5	5·0	...
10	1·0	4·5	...
15	0·5	5·5	...

Complete the table, then plot W and H and W and $\sqrt{H}$. State conclusions.

Obtain the quantity of water discharged in cubic feet per second, then using the formula $Q=KA\sqrt{2gh}$ determine the average value of K the coefficient of discharge.

NOTE.—The area must be expressed in square feet.

Example 6.—The head of water in a tank is kept at 16 ft., and water is discharged through a circular orifice, 1 in. diameter, at the bottom of the tank. Determine the discharge from the tank in gallons per minute. Coefficient of discharge=0·62.

In the formula $Q=KA\sqrt{2gH}$ the quantity Q is expressed in cubic feet per second. Using the formula to determine Q, and converting the result into gallons per minute, we have

$$Q=\frac{0\cdot62\times0\cdot7854\times32\times62\cdot5\times60}{144\times10}=40\cdot58.$$

SEVENTH SET OF EXAMPLES

1. Prove that the pressure at any point in a liquid varies with the depth.

What head of water will produce a pressure of 14·7 lbs. per sq. in. ?

2. A swimming-bath is 90 ft. long and 30 ft. wide, and the bottom slopes uniformly so that the depth of water at one end is 3 ft., that at the other end being 6 ft. Determine the difference, in tons, between the thrusts due to the water on each end. (1 cub. ft. of water weighs 62·5 lbs.)

3. The dimensions of a vertical rectangular sluice gate are 8 ft. by 4 ft., and it is submerged 2 ft. below the surface of the water with its longer side parallel to the surface. Determine the position of the centre of pressure. (1 cub. ft. of water weighs 62·5 lbs.)

4. Define density and specific gravity.

Describe experiments by means of which you would determine the specific gravity of (*a*) a solid, (*b*) a liquid.

5. What is meant by the pressure at a point in a liquid? Upon what factors does the pressure at a given point in a liquid depend when the liquid is at rest and subject to the earth's attraction? L.M.

6. Find the relative density of sand compared with water at the temperature of the experiment from the following data :—

Mass of specific gravity bottle empty, 23·32 grm.

Mass of specific gravity bottle partly filled with sand, 81·69 grm.

Mass of specific gravity bottle containing the sand and filled up with water, 109·66 grm.

Mass of specific gravity bottle filled with water alone, 73·53 grm. L.M.

7. A solid iron pillar 6 ft. long, 1 ft. wide, and 6 in. thick is found to weigh 1,460 lbs. Determine (*a*) the density, (*b*) the specific gravity of iron. (1 cub. ft. of water weighs 62·5 lbs.)

How would you determine experimentally the specific gravity (*a*) of glycerine, (*b*) of lead shot? N.M.

8. Obtain an expression for the tension in a string which supports a body at a given depth in water (*a*) when the body sinks in water, (*b*) when the body floats on water.

A piece of cork weighing 1 lb. is attached by a string to the bottom of a vessel containing water, the cork being wholly immersed. Determine the tension in the string. (Specific gravity of cork=0·25.)

9. Explain the meaning of the expression "coefficient of discharge of an orifice."

An orifice, 1 in. diameter discharges, 19·6 gals. of water per minute under a head of 4 ft. Calculate the coefficient of discharge of the orifice.

State how you would measure the discharge when making an experiment. U.L.C.I.

10. Determine the average coefficient of discharge of a sharp-edged circular orifice, $\frac{3}{8}$ in. diameter, from the following data, the head of water over the orifice being kept constant while each observation was made :—

Number of observation .	1	2	3
Head of water (inches) .	33·4	27·2	21·3
Weight of water discharged per minute (lbs.)	23·5	21	19

U.L.C.I.

11. Determine the head of water which will give a discharge of 248 cub. ft. in half an hour through a square-shaped orifice of 1 in. side. (Coefficient of discharge=0·62.)

CHAPTER IX

THERMOMETRY. EFFECTS OF HEAT ON SOLIDS, LIQUIDS, AND GASES

THE early scientists thought that heat, to which they gave the name " caloric," was a fluid substance which could be poured from one body to another just as we pour water, and the theory was thought to be correct until the end of the eighteenth century. About that time an American, Count Rumford (1753-1814), and Davy (1778-1829) carried out experiments from which they concluded that heat was not a material substance but that it could only be produced when work was done. A Manchester man, James Prescott Joule (1818-89), confirmed the conclusions arrived at by Rumford and Davy, and continued his experiments, which enabled him to establish the modern view that heat is energy and is due to the vibrations of the molecules composing a substance. This was done in 1849, when Joule not only stated that heat was energy, but he also stated the amount of heat that could be produced by a given amount of work.

We shall return to this important relationship, and shall discuss the units in which we measure heat later. In the meantime we have to consider temperature and the general effects of heat.

We define temperature as the particular state of a substance due to the heat it contains. The instrument for measuring temperature is the thermometer, the first being made by Galileo in 1597. For engineering work two scales of temperature are in general use. Fahrenheit (1686-1736) gave his name to one, and Celsius (1701-44) invented the centigrade thermometer. In the former the freezing-point of water is marked 32° and the boiling-point is 212°, the corresponding points on the centigrade thermometer being marked 0° and 100°.

EXPERIMENT 21. *To Compare the Centigrade and Fahrenheit Thermometers and to obtain a Formula by Means of which One* *could Convert Readings from One Scale to the Other.*—Place a Fahrenheit and centigrade thermometer in a vessel containing water and note the temperature on each thermometer. By means of a Bunsen burner heat the water slowly, and for every 5° on the centigrade scale note the corresponding Fahrenheit readings.

Plot these readings, centigrade horizontally, and obtain a law of the form $F=aC+b$ by finding the constants a and b. In this law F denotes Fahrenheit readings and C centigrade readings, and the relation may be used to convert from one scale to the other (Fig. 98).

Having obtained the law in the above form it will be convenient to rearrange it and remember it in the form

$$\frac{F-32}{9}=\frac{C}{5}.$$

Mercury possesses certain advantages for use as the working substance in a thermometer. It remains liquid over a wide range in temperature, and expands and contracts fairly uniformly with a variation in temperature. It does not adhere to the sides of a glass tube, and being very opaque it is easy to see a very thin column.

Example 1.—Mercury boils at 357° C. State this temperature on the Fahrenheit scale.

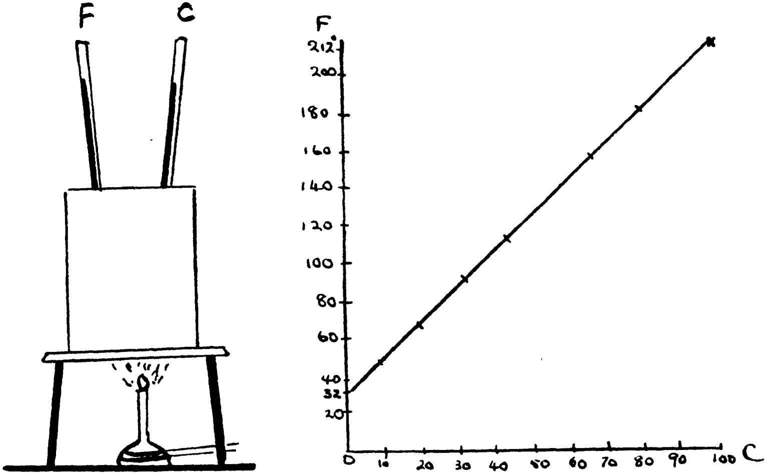
Substituting 357° for C in the formula $\frac{F-32}{9}=\frac{C}{5}$, we have

$$\frac{F-32}{9}=\frac{357}{5}, \text{ or } 5F-160=3213,$$

whence $$F=674{\cdot}6^\circ.$$

There are occasions when it is necessary to know the highest and lowest temperatures reached during a given period, a common form of thermometer for this purpose being Six's self-registering maximum and minimum thermometer, which is shown in Fig. 99.

Alcohol is the working substance used in this thermometer, any errors due to the unequal expansion of the substance being negligible within the range of temperature for which the instrument is generally used.



C	F
5	41
10	50
15	59
20	68
25	77
30	86
⋮	⋮
100	212

FIG. 98.

In Fig. 99 the spaces A, B, and C are filled with alcohol, while mercury fills the U part of the thermometer. The alcohol in the parts A and C will expand with an increase in temperature and contract as the temperature falls, and this expansion or contraction will alter the end positions of the mercury column. A small index is placed in B and C, the highest position reached by that in B indicating the maximum temperature reached during a certain period. On the other hand, if the temperature should fall, the mercury column will rise in C and push the index before it, the highest position reached indicating the lowest temperature. To set the instrument it is tapped gently so that each index rests on the top of the mercury columns.

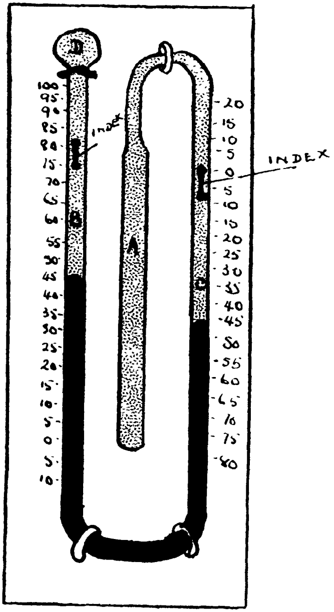


Fig. 99.

General Effects of Heat

Generally, when heat is applied to a solid the solid expands, but there are one or two exceptions to this general rule. Ice, for example, is a solid which contracts under the influence of heat, 12 cub. in. of ice when completely melted contracting to 11 cub. in. of water. We shall discuss further the behaviour of ice and water under the influence of heat presently.

Our next consideration here is the effect of heat on metals, and, as you know, the engineer has to make provision for their expansion and contraction under seasonal variations of temperature. To mention one or two common examples, we have the holding together of the sides of a house by means of metal bars when the sides of the house start to bulge ; in roof trusses and metal bridges the engineer fixes one end and allows the other end to rest on rollers so as to allow for expansion during the summer months and contraction during the winter months ; for the same reason we often find workmen adjusting the space between consecutive railway lines when the lines are laid above ground.

Within moderate ranges of temperature the properties of metals do not show troublesome variation, but they may be entirely changed by the application of intense heat. For example, the variation in the strength of a mild-steel bar, such as the structural engineer would use, is shown in Fig. 100.

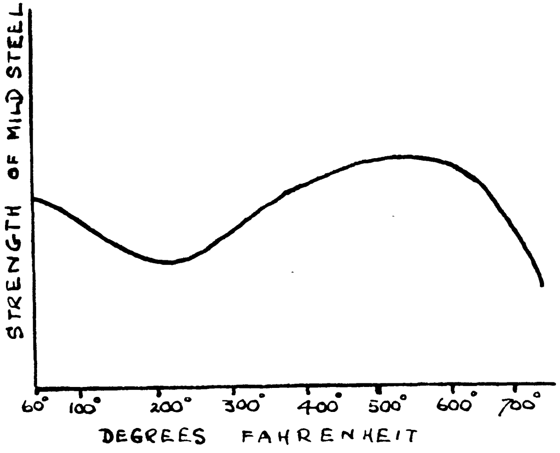


Fig. 100.

From the graph it will be noticed that as the temperature rises from 60° to about 240° F. the strength decreases, but that it starts to increase again until the temperature is about 580° F., when its strength is slightly greater than it was originally. From about 600° F. onwards there is a rapid drop in strength, and this to some extent explains why metals generally become twisted during a fire.

The electrical resistance of a conductor to the flow of a current through it is affected by temperature, an increase in temperature causing an increase in the resistance. For example, if R_0=resistance of a conductor at 0° C. and R_T =resistance at a temperature T°, then $R_T=R_0(1+\alpha T)$

where α is a constant quantity for the conductor known as the temperature coefficient.

EXPANSION OF SOLIDS

Suppose we have a piece of metal unit length at 0° C. and we heat it to 1° C., its length then being $1+a$, its length at 2° C. will be $1+2a$, and so on. If instead of taking a piece of metal of unit length we take a length L_0 at 0° C. and we heat this to a temperature T° C., its length will then be L_0+L_0aT, *i.e.*, if L_T=length at T° C., then we can write $L_T=L_0+L_0aT$, or $L_T=L_0(1+aT)$, which expression may also be written as $a=\frac{L_T-L_0}{L_0T}$. The quantity a is a constant for a particular metal and is known as the coefficient of linear expansion. In words we can define it as the increase in length per unit length per unit change in temperature, and the formula may be used to determine any one quantity if the remaining quantities are known.

Next suppose we take a thin square sheet of metal of unit side at 0° C. and we heat it to 1° C. By the above argument its side will become $1+a$ and its area will be $(1+a)^2$ or $1+2a+a^2$. Now a is a small quantity and a^2 is obviously smaller (the mathematician would say that it is of the second degree of smallness), and for all practical purposes we can neglect it, and we can call the new area $1+2a$. By similar reasoning to the case of linear expansion we can say that if A_0=area of a metal at 0° C. and A_T=area at a temperature T° C., then $A_T=A_0(1+2aT)$, and from this relation we can state that the coefficient of areal expansion is twice the coefficient of linear expansion.

Finally, consider a cube of unit side at 0° C., *i.e.*, its volume will be unity. If the cube is heated to 1° C. each side will become $1+a$, so that the volume at 1° C. will be $(1+a)^3$ or $1+3a+3a^2+a^3$. Again we can neglect the small quantities $3a^2$ and a^3 and state that the new volume is $1+3a$. Therefore, if V_T=volume of a metal at T° C. and V_0=volume at 0° C., we can write $V_T=V_0(1+3aT)$. The term $3a$ is a constant c called the coefficient of cubic expansion, whose value for all practical purposes is three times the coefficient of linear expansion.

EXPERIMENT 22. *To Find the Coefficient of Linear Expansion of a Metal Rod.*—One form of apparatus used for this experiment is shown in Fig. 101. The length of the rod is obtained at the temperature of the inlet water. Steam entering the water as shown will, of course, cause an increase in temperature, and therefore an increase in length of the rod, this increase in length being measured by means of a spherometer placed on the top of the apparatus. The value of the coefficient of expansion may then be obtained from the relation

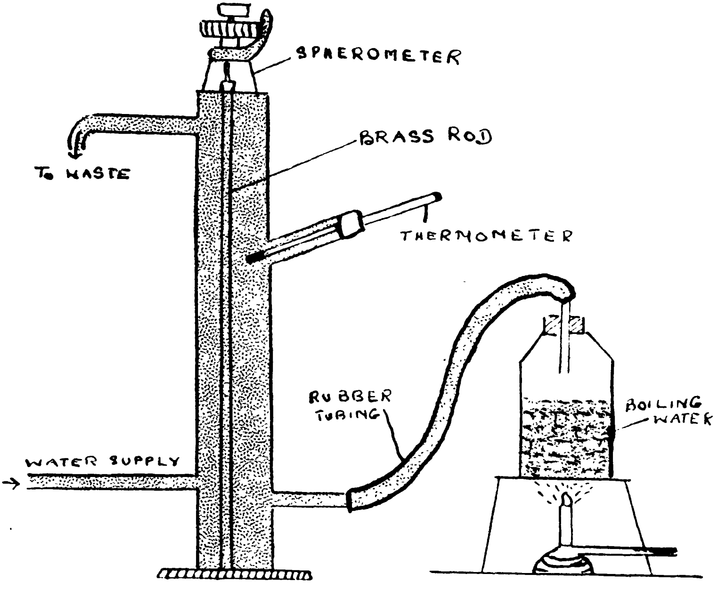


FIG. 101.

$$\text{coefficient of linear expansion}=\frac{\text{increase in length}}{\text{original length}\times\text{rise in temp.}}.$$

Determine the coefficient of expansion of brass from the following observed values obtained with an apparatus, as shown in Fig. 101 : Length of brass rod=77·6 cm. at temperature of inlet water, viz., 19·8° C. Increase in length as measured by the spherometer when the temperature of the water rose to 95° C.=0·15 cm.

EXPANSION OF LIQUIDS

In dealing with the expansion of a liquid we have to take into consideration the expansion of the containing vessel, and for that reason the problem is a little more complicated than is the case with a solid. If you place a quantity of liquid in a vessel, such as that shown at A (Fig. 102), and you apply heat to the vessel, you will notice that the liquid first drops a little in the stem and then commences to rise as the heat is continued. In such a case the expansion of the liquid is said to be apparent. We shall discuss methods of determining the apparent and real expansion of liquids shortly, our next consideration here being the behaviour of water under seasonal differences in temperature.

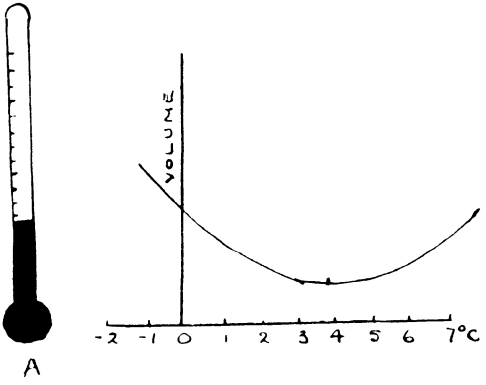


FIG. 102.

If you know the volume of the bulb of the instrument shown at A (Fig. 102), and you place one-seventh of this volume of mercury in the bulb, you can overcome the difficulty due to the expansion of the glass, *i.e.*, the expansion of the water will be its real expansion.

Suppose the stem of the instrument to be graduated to read volumes and you start with a given volume of water at 0° C. Gently heat the bulb to about 10° C. and note the volume for every degree rise. If you plot temperature horizontally and volume vertically, you will obtain a graph similar to that shown in Fig. 102. From the graph we notice that as the temperature rises from 0° to 4° C. the volume decreases, but from 4° C. onwards the volume again increases. You know that the density of a substance is the ratio $\frac{\text{mass}}{\text{volume}}$, so that if the volume of a substance is reduced its density is increased, and from the above graph we can state that since the volume of the water is lowest at 4° C. its density is a maximum. This peculiarity of water is of great importance in nature and accounts for the fact that ice forms on the surface of water and thickens downwards, but below a certain depth the water will never be below 4° C., and so we have the lives of fishes and other aquatic animals preserved.

The density and volume of a given quantity of liquid will vary with the temperature, but the mass of the liquid remains constant. Imagine a liquid of density D_0 and volume V_0 at 0° C., and let D_T represent the density and V_T represent the volume of the liquid at some higher temperature T° C. Then, since the mass is constant, we can write $V_0D_0=V_TD_T$, or $\frac{D_T}{D_0}=\frac{V_0}{V_T}$. But we have already seen that $V_T=V_0(1+CT)$ where C is the coefficient of cubic expansion, so that we now have $\frac{D_T}{D_0}=\frac{V_0}{V_0(1+CT)}=\frac{1}{(1+CT)}$.

The above expression may be written as $D_T=\frac{D_0}{(1+CT)}$, and the student who is familiar with the Binomial Theorem will be able to write it as $D_T=D_0(1-CT)$, from which any one quantity may be determined if the others are known.

A containing vessel is made of some material, the coefficient of expansion of which is C, and it contains a liquid of which the coefficient of *real* expansion is C_R. If $C_R=C$, the liquid will not rise in the vessel when heated. If, however, C_R is greater than C, it will rise, and the expansion is what we have called the apparent expansion. Let C_A=coefficient of *apparent* expansion, then we have $C_A=C_R-C$, or $C_R=C_A+C$. Again, knowing any two of these quantities we can determine the third.

In the early part of the nineteenth century Regnault very carefully carried out experiments in order to determine the coefficient of real expansion of mercury, Fig. 103 showing the principle of his method.

Mercury is poured into the apparatus and rises to the same height in the vertical tubes A and B. Steam is admitted to the steam chest as shown, and heats the mercury in B, causing it to rise to a higher level than that in A. Let the temperature of the mercury in B=T° C., while that of the mercury in the other part of the apparatus=t° C. Let h=height of the two columns when they are at the same initial temperature and H=height to which the mercury rises in B when heated to a temperature T° C., these heights being measured from a fixed datum xy. If D_T=density of the mercury at T° C. and D_t=its density at t° C., then in the state of equilibrium we have

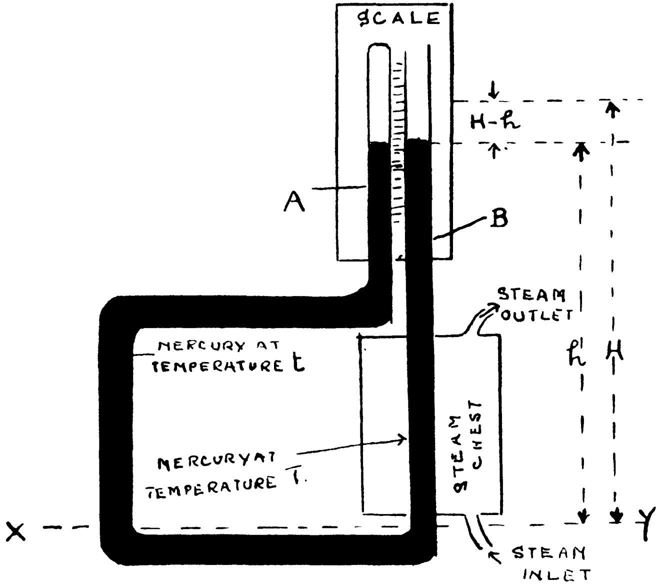


Fig. 103.

$$hD_t = HD_T, \text{ or } \frac{H}{h} = \frac{D_t}{D_T}.$$

But if D_0=density of the mercury at 0° C. and C=its coefficient of *real* expansion we have, as above,

$$\frac{D_t}{D_T}=\frac{D_0(1-Ct)}{D_0(1-CT)},$$

which expression simplifies to $(1-Ct)(1-CT)^{-1}$, or $1+C(T-t)$. We therefore have $\frac{H}{h}=1+C(T-t)$, or $H=h+hC(T-t)$, from which $C=\frac{H-h}{h(T-t)}$.

The coefficient of *apparent* expansion of a liquid may be determined by means of an instrument known as a weight thermometer, shown in Fig. 104.

The instrument is filled with mercury by alternate heating and cooling, being completely filled at 0° C. by placing the thermometer in melting ice.

Suppose W=weight of mercury in the thermometer at 0° C. If the instrument is then heated to a temperature T° C., both the mercury and the bulb will expand, and let the weight of mercury expelled=w, *i.e.*, the weight of mercury in the instrument at T° C. will be $(W-w)$. These weights are proportional to the volumes they occupy, so that if C_A=coefficient of apparent expansion of mercury, we have

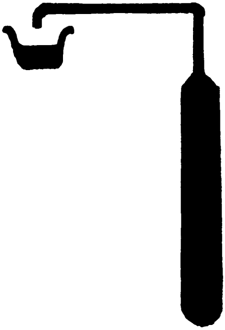


FIG. 104.

$$C_A=\frac{w}{(W-w)T}.$$

If, therefore, we determine C_A as above and we know C_R the coefficient of real expansion of mercury from Regnault's tables, we can determine C the coefficient of expansion of the material of which the thermometer is made from the relation $C_R=C_A+C$. Finally, having obtained the value of C, we can determine C_A for any other liquid, as described above, and we can then calculate the value of C_R from the same relation.

EXPERIMENT 23. *To Find the Coefficient of Apparent Expansion of Water in Glass.*—The following readings refer to a weight thermometer, shown in Fig. 104.

Weight of thermometer empty =12·95 grm.
Weight of thermometer+water =23·25 grm.

Therefore weight of water in the instrument=10·3 grm.

The thermometer was placed in a quantity of water at 14° C., and the water was heated to a temperature of 92° C. After the experiment the instrument was again weighed, its weight then being 23 grm., *i.e.*, the weight of water expelled =0·25 grm. From these readings determine the coefficient of apparent expansion of water.

Example 2.—A weight thermometer weighs 50 grm. when empty and 650 grm. when full of mercury at 0° C. It is heated to a temperature of 100° C. and a quantity of mercury is expelled. If the coefficient of real expansion of mercury is 0·000181, and the coefficient of cubic expansion of glass is 0·000027, determine the weight of mercury expelled. What is the coefficient of linear expansion of glass ?

From the relation $C_R = C_A + C$ we have

$$C_A = 0{\cdot}000181 - 0{\cdot}000027 = 0{\cdot}000154,$$

and substituting this value in the formula $C_A = \dfrac{w}{(W-w)T}$,

we can write $0{\cdot}000154 = \dfrac{w}{(600-w)100}$, *i.e.*, $9{\cdot}24 - 0{\cdot}0154w = w$,

whence w, the weight of mercury expelled=9·1 grm.

Coefficient of linear expansion $= \frac{1}{3}$ coefficient of cubic expansion

$$= \tfrac{1}{3} \times 0{\cdot}000027 = 0{\cdot}000009.$$

EXPANSION OF GASES

In dealing with this subject we have three cases to consider :

1. The relation between the pressure and volume of a gas at constant temperature.
2. The relation between the volume and temperature of a gas at constant pressure.
3. The relation between the pressure and temperature of a gas at constant volume.

These three conditions ought to be investigated by experiment, and the conclusions should be remembered.

EXPERIMENT 24. *To Investigate the Relationship between the Pressure and Volume of a Gas kept at a Constant Temperature.*—Fig. 105 shows the apparatus to be used in this experiment. One of the tubes is closed, the other being open, and the two are connected by means of rubber tubing. Mercury is poured into the apparatus, and when it stands at the same level in both tubes the pressure of the air in the closed tube will be equal to the atmospheric pressure. The pressure and volume are varied by raising or lowering the open tube.

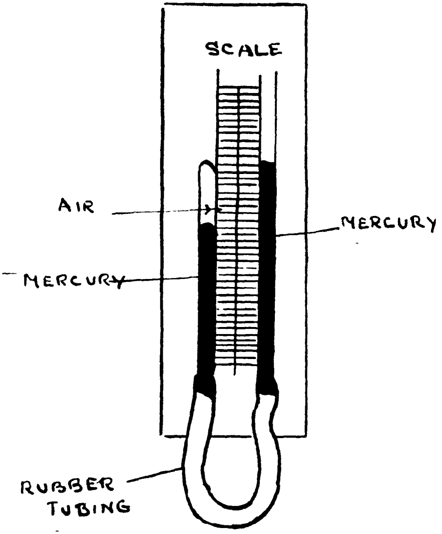


FIG. 105.

NOTE.—In this experiment the volume of air in the closed tube is represented by length.

The following readings were taken when the atmospheric pressure was 74·93 cm. :—

Difference in Level between Mercury Columns.	Pressure P = Height of Barometer ± Difference in Level.	Volume of Air in Closed Tube V.	P×V.
Cm.	Cm.		
3·5	71·43	43·0	3,070
1·0	73·93	41·5	...
0·0	74·93	41·0	...
8·0	82·93	37·0	...
27·5	102·43	30·0	...

Complete the last column in the above table, then for each pressure determine the value of $\frac{1}{V}$. Plot pressure vertically and $\frac{1}{V}$ horizontally, and state conclusions.

The above investigation was first carried out by Robert Boyle (1627-91), and the conclusion is known as Boyle's Law, which states that if the temperature of a gas remains constant the volume is inversely proportional to the pressure, or, in other words, if the temperature of a gas is constant the product pressure × volume is a constant quantity.

EXPERIMENT 25. *To Investigate the Relationship between the Volume and Temperature of a Gas at Constant Pressure.*—The apparatus for this experiment is shown in Fig. 106. When the mercury stands at the same level in the two arms, as sketched, the pressure of the air in the closed part of the apparatus will be equal to the atmospheric pressure in the open part. This part of the apparatus is placed in a quantity of water which can be heated by steam passing through the bent tube shown. The volume of the enclosed air can be read off from a suitable scale, and when this is heated by the surrounding water it will, of course, expand and will depress the column of mercury in this column. Mercury is then drawn off by means of the small tap at the bottom of the apparatus until it again stands at the same level in both arms, *i.e.*, we have an increased volume at the same pressure. The volumes and temperatures are then noted for every few degrees rise, the following table showing actual readings obtained with this apparatus :—

Temperature, ° C.	17·5	25	33	41	47	52	58
Volume, c.c.	25·5	27·5	28	28·9	29·2	29·8	30·5

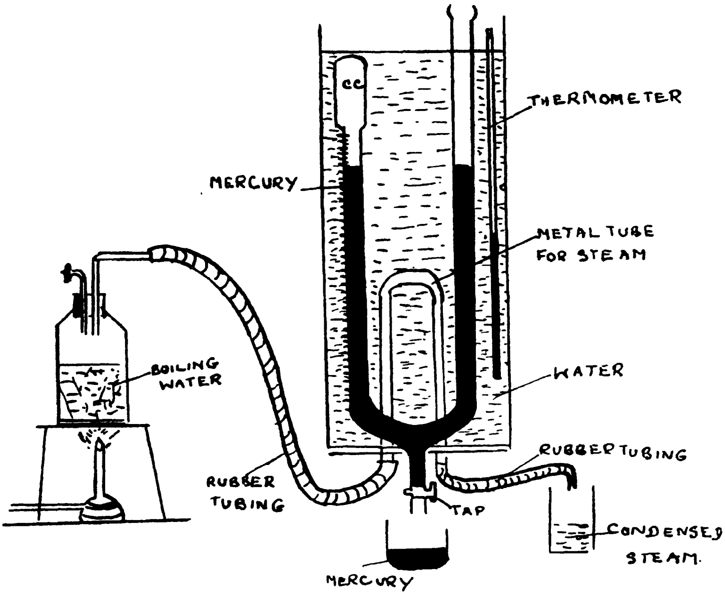


Fig. 106.

Select any two values of volume and temperature from this table and determine the value of the coefficient of expansion of air from the relation coefficient of expansion

$$=\frac{\text{increase in volume}}{\text{original volume}}\times\frac{1}{\text{rise in temperature}}.$$

The original investigator of this relationship was Charles (1746-1823), and the result is known as Charles's Law, which states that the volume of a given quantity of gas increases by

$\frac{1}{273}$ of its volume at 0° C. for each degree rise in temperature, the pressure remaining constant.

EXPERIMENT 26. *To Investigate the Relationship between the Pressure and Temperature of a Gas at Constant Volume.*—The apparatus for this investigation is sketched in Fig. 107.

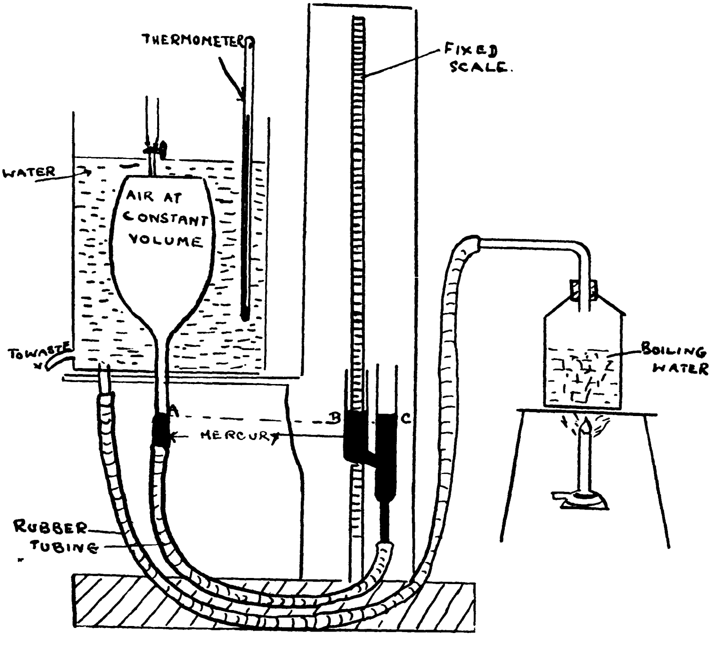


FIG. 107.

First of all adjust the apparatus so that the mercury levels A, B, and C are in one horizontal line and note the temperature of the water. As the water is heated A will be lowered and B and C will be raised, but when the readings of temperature and pressure are taken the mercury level A must be brought back to its original position so that the difference between A and the levels of B and C will indicate the increase in pressure due to the increase in temperature of the air in the enclosed space. The total pressure will be this difference in level plus the atmospheric pressure.

The following table shows the results of an experiment, the height of the barometer at the time being 74·9 cm. :—

Difference in Level.	Height of Barometer.	Total Pressure of Mercury.	Temperature.
Cm.	Cm.	Cm.	° C.
0·0	74·9	74·9	14·2
3·9	74·9	78·8	26·0
7·3	74·9	82·2	38·5
9·8	74·9	84·7	49·0
12·6	74·9	87·5	60·0

To find the coefficient of increase of pressure from these readings, take any two temperatures and the corresponding total pressures. Suppose $t°$ and T are the temperatures, the corresponding pressures being P_t and P_T. If β=the required coefficient of increase of pressure, we can write $P_t=P_0(1+\beta t)$ and $P_T=P_0(1+\beta T)$ where P_0=pressure at 0° C. We therefore have

$$\frac{P_T}{P_t}=\frac{P_0(1+\beta T)}{P_0(1+\beta t)}=\frac{1+\beta T}{1+\beta t}.$$

Make the necessary substitutions and determine the value of β.

The result of this experiment is known as the Law of Pressures, which states that the pressure of a gas at constant volume increases by $\frac{1}{273}$ of its pressure at 0° C. for each degree rise in temperature.

According to Charles's Law 1 c.c. of air at 0° C. will become $1+\frac{1}{273}$ c.c. at 1° C., $1+\frac{10}{273}$ c.c. at 10° C., and $1-\frac{100}{273}$ c.c. at $-100°$ C. Theoretically 1 c.c. of air at 0° C. would be reduced to nothing at a temperature of $-273°$ C. In practice, however, this would not happen, because long before this temperature was reached the air would change its state, first it would liquefy, and eventually solidify.

Temperatures reckoned from $-273°$ C., which temperature is known as the absolute zero, are said to be measured on the absolute scale. Fig. 108 shows the Absolute and Centigrade scales. As you know, the freezing-point of water is 0° C., but on the absolute scale it would be given as 273°, the boiling-point of water on this scale being 373°.

A gas can be liquefied by pressure provided the gas is below what is called its critical temperature, and the temperature at which one or two common gases liquefy is shown in Fig. 108. For example, air liquefies at −186° C. or 87° absolute, and at this very low temperature the physical properties of a body are entirely changed. Substances which are normally very tough become extremely brittle. The specific heat of a substance is lowered, and it has been found that carbon has a very small specific heat at the temperature of liquid air. The electrical resistance of a conductor is also greatly reduced at this low temperature.

After hydrogen helium is the lightest known gas, and it is liquefied by being cooled in liquid hydrogen and then being allowed to expand suddenly, but as it is very expensive to produce in quantity it is not yet used commercially, except in Germany, where it has been used in Zeppelins.

Boyle's Law states that the pressure of a gas varies inversely as its volume, and Charles's Law states that the volume of a gas varies directly as its *absolute* temperature, so that if P=pressure of a gas, V=volume, and T=temperature (absolute) the two laws may be combined in a general statement such as $\frac{PV}{T}$=a constant quantity C, and this statement is known as the general gas relationship. For example, suppose P_1, V_1, and T_1 to be the first state of a gas with regard to pressure, volume, and absolute temperature, and let P_2, V_2, and T_2 be the second state, then $\frac{P_1V_1}{T_1}=\frac{P_2V_2}{T_2}$, from which we can determine any one quantity if the remaining quantities are known.

NOTE.—If pressure volume or temperature is constant in any particular case it is simply cancelled out on both sides of the above relation.

Example 3.—The volume of a gas at 32° F. is 10 cub. ft. Determine its volume at the boiling-point of water, the pressure remaining constant.

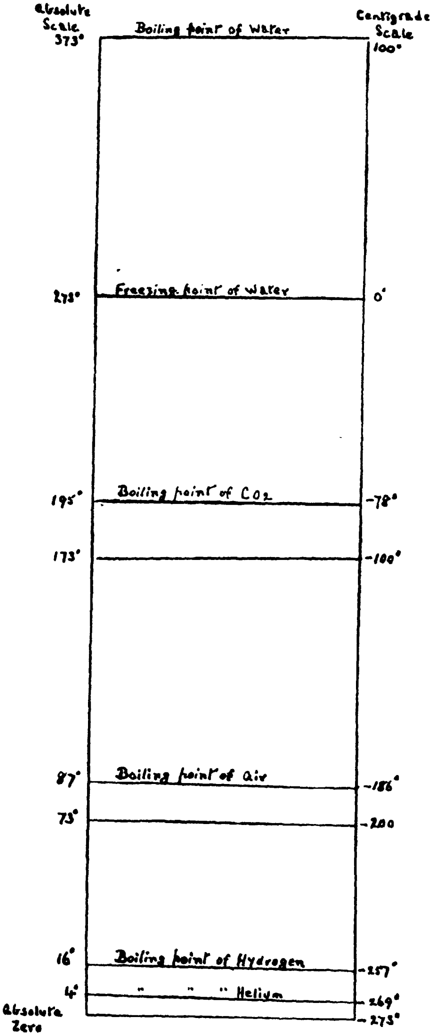

Absolute Scale
373°
Boiling point of Water
Centigrade Scale
100°
273°
Freezing point of Water
0°
195°
Boiling point of CO_2
-78°
173°
-100°
87°
Boiling point of Air
-186°
73°
-200
16°
Boiling point of Hydrogen
-257°
4°
" " " Helium
-269°
Absolute Zero
-273°

Fig. 108.

In the general gas relation $\frac{P_1V_1}{T_1}=\frac{P_2V_2}{T_2}$, since the pressure is constant we can write $\frac{V_1}{T_1}=\frac{V_2}{T_2}$. The absolute zero in Fahrenheit units $=-460$ (approx.), so that $T_1=32+460=492$ and $T_2=212+460=672$. Substituting the given values we have $\frac{10}{492}=\frac{V_2}{672}$, whence the required volume $V_2=\frac{6720}{492}$ $=13{\cdot}67$ cub. ft.

Example 4.—The cylinder of a gas engine is 8 in. diameter, the piston stroke is 18 in., and the clearance volume is 250 cub. in. At the beginning of the compression stroke the temperature of the gas is 100° C., and the pressure is atmospheric, viz., 14·7 lbs. per sq. in. If the pressure of the gas is 120 lbs. per sq. in. at the end of the compression stroke, determine the final temperature.

Volume moved through by the piston $=\frac{3{\cdot}142\times64\times18}{4}$ $=904{\cdot}8$ cub. in., so that total volume at the beginning of the stroke $V_1=904{\cdot}8+250=1154{\cdot}8$ cub. in. The final volume V_2=clearance volume=250 cub. in., so that substituting the known values in the formula, we have

$$\frac{14{\cdot}7\times1154{\cdot}8}{373}=\frac{120\times250}{T_2}$$

where T_2 is the required absolute temperature, *i.e.*,

$$T_2=\frac{30000\times373}{14{\cdot}7\times1154{\cdot}8}=659{\cdot}1^\circ.$$

The temperature on the centigrade scale is therefore

$$659{\cdot}1-273=386{\cdot}1^\circ.$$

EIGHTH SET OF EXAMPLES

1. Explain the advantages of mercury for use as a thermometric substance.

(*a*) Convert the following centigrade readings to the Fahrenheit scale :—

30°, 90°, 124°, 200°, 360°, −10°, −62°, −100°.

(*b*) Convert the following Fahrenheit readings to the centigrade scale :—

41°, 77°, 132·8°, 215·6°, 320°, 21·2°, −9·4°, −112°.

(*c*) At what temperature will both scales give the same reading ?

2. The following table shows the melting-point in Fahrenheit degrees of various substances. State the corresponding centigrade readings :—

Substance.	Platinum.	Wrought Iron.	Copper.	Lead.	Tallow.
Melting-point, ° F.	3,110	2,912	2,160	600	36

3. Define the term coefficient of linear expansion. Describe an experiment to show that the coefficient of linear expansion of copper is greater than that of steel.

The length of a certain copper rod is 30 in. at 0° C. What is the length of steel rod at 0° C. that has the same length as the copper rod at 100° C. ?

(The coefficients of linear expansion of copper and steel are 0·000018 and 0·000012 respectively.) L.M.

4. Rods of brass and wrought iron are each 36 in. long at 60° F. What will be the difference between their lengths at 212° F. ?

Coefficients of linear expansion per degree Fahrenheit, brass, 0·00001075 ; wrought iron, 0·00000656. U.L.C.I.

5. A U-tube containing oil has one limb surrounded by a wider tube. Describe what occurs when steam is blown through the wide tube and explain what may be deduced from such an experiment. L.M.

6. A specific gravity bottle weighs 34·62 grm. when empty, 160·75 grm. when filled with a liquid at 20° C., and 155·81 grm. after some of the liquid has been expelled by heating to 100° C. Find the coefficient of expansion of the liquid, the coefficient of cubic expansion of glass being 0·000026. L.M.

7. Describe apparatus suitable for determining the relation between the pressure and temperature of a mass of gas kept at constant volume. If the gas indicates a pressure of 75 cm.

of mercury when immersed in a vessel containing melting ice, and a pressure of 54·5 cm. when the ice is replaced by a certain liquid, find the temperature of this liquid. L.M.

8. Distinguish between the coefficients of apparent and real expansion of a liquid. Describe in detail how you would determine the coefficient of apparent expansion of mercury by means of a weight thermometer.

9. Explain the meaning of the expression "coefficient of expansion of a gas."

Supposing that a gas were to occupy 500 c.c. at 80° C. and 600 c.c. at 120° C., what would be its coefficient of expansion, assuming the gas to expand uniformly? L.M.

10. A volume of 1,000 cub. ft. of air at atmospheric pressure (14·7 lbs. per sq. in.) and at a temperature of 10° C. is compressed to an absolute pressure of 130 lbs. per sq. in. and a volume of 140 cub. ft. Find the temperature of the air after compression. The compressed air is stored in a vessel, but before it is used the temperature falls to 40° C.; find the pressure of the air then available. U.L.C.I.

11. A quantity of air occupies 1,000 c.c. at 10° C. At what temperature will its volume be doubled at constant pressure?

12. State briefly how the volume of a gas is affected (*a*) by alteration of pressure, (*b*) by alteration of temperature. A volume of 100,000 cub. ft. of air per minute passes down a mine shaft at a temperature of 50° F. and is heated in the workings to a temperature of 75° F. What will be the volume of this air coming out of the mine, assuming the pressure to remain constant? U.L.C.I.

13. What is the relation connecting the pressure, the volume, and the temperature of a quantity of air or other "permanent" gas?

A quantity of air has a volume of 200 c.c. when its pressure is 76 cm. of mercury and its temperature 15° C. What will be its temperature when its volume is 193 c.c. and its pressure 100 cm.? L.M.

14. Four hundred cubic feet of air at an absolute pressure of 15 lbs. per sq. in. and at a temperature of 10° C. are compressed into a volume of 90 cub. ft. at a pressure of 100 lbs. per sq. in. absolute. Find the final temperature of the air. U.L.C.I.

CHAPTER X

MEASUREMENT OF HEAT. HEAT AND WORK. HEAT TRANSMISSION

THERE are three units in general use in which quantities of heat may be measured. The physicist uses what is called the gramme-calorie, or simply the calorie, and this is defined as the quantity of heat necessary to raise the temperature of 1 grm. of water through 1 centigrade degree. This unit of heat is very rarely used by the engineer. He uses either the pound-calorie or centigrade heat unit (C.H.U.), which is defined as the quantity of heat necessary to raise the temperature of 1 lb. of water through 1 centigrade degree, or he uses what is termed the British Thermal Unit (B.Th.U.), which is defined as the quantity of heat necessary to raise the temperature of 1 lb. of water through 1 Fahrenheit degree.

In this work we shall use all three units.

The ratio

$$\frac{\text{Amount of heat required to raise unit mass of a substance through } 1^\circ}{\text{Amount of heat required to raise unit mass of water through } 1^\circ}$$

is defined as the specific heat of the substance, but since by definition the amount of heat required to raise unit mass of water through 1° is 1 heat unit, we can define the specific heat of a substance as the amount of heat required to raise unit mass of the substance through 1°.

Suppose S=amount of heat required to raise 1 grm. of a substance through 1°, then the amount of heat required to raise M grm. of the substance through 1° will be MS units, and the amount required to raise M grm. of the substance from a temperature T_1° to T_2° will be $MS(T_2-T_1)$ units. We can express this result in words by saying that the product mass of a substance × specific heat of the substance × change in temperature represents the heat gained or lost, depending on whether the temperature is increased or decreased. This relation is the foundation for all questions on heat measurement and should be remembered.

In order to determine the specific heat of a substance we use an apparatus such as that shown in Fig. 109. A substance of known mass M is heated to a temperature of 100° C. by being left for a few minutes in a quantity of boiling water. It is then transferred quickly into a measured quantity of water contained in a calorimeter, and the calorimeter is placed in another vessel and padded with cotton wool in order to prevent loss of heat by radiation. Heat will pass from the piece of metal to the water and calorimeter, the increase in temperature being measured by means of the thermometer.

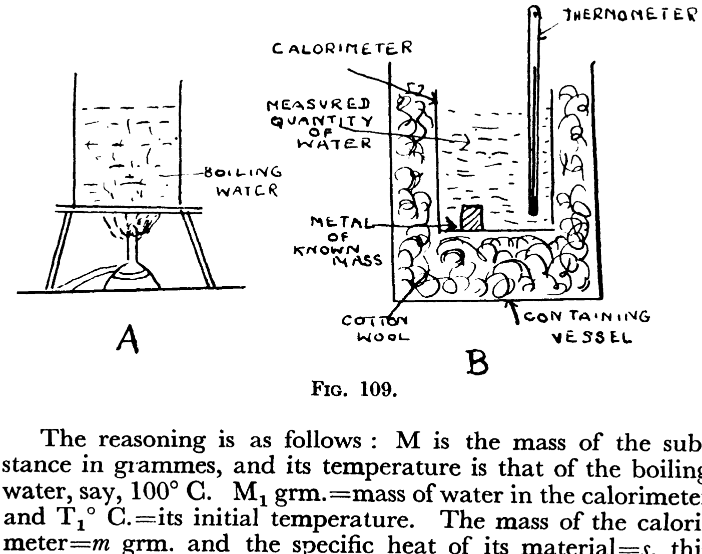


FIG. 109.

The reasoning is as follows : M is the mass of the substance in grammes, and its temperature is that of the boiling water, say, 100° C. M_1 grm.=mass of water in the calorimeter and T_1° C.=its initial temperature. The mass of the calorimeter=*m* grm. and the specific heat of its material=*s*, this quantity being known. Let the heat from the metal cause the temperature of the water and the calorimeter to rise to, say, T_2° C. Then we have heat lost by metal=heat gained by water and calorimeter, assuming no loss. The final temperature of the metal will, of course, be the same as the final temperature of the water and containing vessel, viz., T_2° C. Heat lost by the metal=$MS(100-T_2)$ where S=the required specific heat. Heat gained by the water=$M_1(T_2-T_1)$, the specific heat of water being unity. The quantity of heat gained by the calorimeter will be $ms(T_2-T_1)$. Our required equation in order to determine S is therefore

$$MS(100^\circ-T_2)=M_1(T_2-T_1)+ms(T_2-T_1),$$

or

$$MS(100^\circ-T_2)=(M_1+ms)(T_2-T_1).$$

In the above relation the quantity ms is known as the *water equivalent* of the apparatus, *i.e.*, it is the extra quantity of water we should have in the apparatus if none of the heat were absorbed by the apparatus.

EXPERIMENT 27. *To Determine the Specific Heat of Lead.*—The apparatus used is shown in Fig. 109, and the following values were obtained :—

A piece of lead mass 38·5 grm. was placed in a quantity of water boiling at 100° C. The weight of the calorimeter was 22 grm. and its water equivalent was 2·2 grm. The calorimeter contained 100 grm. of water at 17° C., and after the lead had been transferred from the boiling water to the water in the calorimeter the temperature of the latter rose to 18° C. Determine the specific heat of lead.

If we require the specific heat of a liquid, the same apparatus may be used as in the previous experiment, and the reasoning is the same, the only difference being that we must know the specific heat of the metal used, and instead of a measured quantity of water in the calorimeter we must have a known quantity of the liquid of which we require the specific heat. In words we can state the relationship as follows : Mass of metal × specific heat (known) × change in temperature = mass of liquid × specific heat of liquid (unknown) × change in temperature + mass of calorimeter × specific heat of its material (known) × change in temperature. Using the above reasoning we can obtain an equation in which the unknown quantity is the required specific heat of the liquid.

EXPERIMENT 28. *To Determine the Specific Heat of Paraffin Oil.*—

Mass of calorimeter = 36·8 grm.
Mass of calorimeter + paraffin oil = 87·3 grm.
Determine mass of oil.

A piece of brass mass 26·3 grm. (specified heat of brass = 0·095) was transferred from water boiling at 100° C. and placed into the paraffin oil, the temperature of which was 16° C. After the experiment the temperature of the oil rose to 21° C. Water equivalent of the apparatus$=3{\cdot}6$ grm. Determine the specific heat of paraffin oil.

Example 1.—A glass bulb containing mercury is heated to a temperature of 112° C. It is then dropped into a vessel containing 120 grm. of water at 8° C., and it causes the temperature of the water to rise to 12° C. If the water equivalent of the vessel is 10 grm., determine (1) the weight of the glass bulb, (2) the weight of the mercury, the combined weight being 50 grm. (Specific heats : Mercury$=0{\cdot}03$, glass$=0{\cdot}19$.)

Let x grm.=weight of the glass bulb, then $(50-x)$ grm. =weight of the mercury. Heat lost by the bulb and the mercury=heat gained by the water and containing vessel neglecting loss. The temperature of the glass and mercury drops from 112° to 12° C., so that the heat lost will be $\{0{\cdot}19x+0{\cdot}03(50-x)\}100$. The temperature of the water and containing vessel rises from 8° to 12° C., so that the heat gained will be $(120+10)4$.

Our equation is therefore

$$\{0{\cdot}19x+0{\cdot}03(50-x)\}100=(130)4=520,$$

from which we find $x=23\frac{1}{8}$ grm. Weight of mercury is therefore $50-23\frac{1}{8}+26\frac{7}{8}$ grm.

Specific Heat of a Gas

The amount of heat required to raise unit mass of a gas through 1° will depend on whether the pressure or the volume of the gas is constant. This means that a gas has two specific heats, one at constant pressure and the other at constant volume.

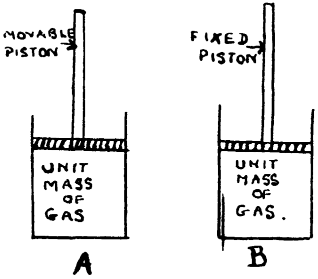


Fig. 110.

In Fig. 110 A represents unit mass of a gas which occupies a certain volume of a cylinder to which is attached a movable piston. As heat is applied to the gas it will, of course, expand and lift the piston, the pressure on which we will assume to be constant. This means that part of the heat sup to the gas is utilised in doing external work, so that only the remainder of the heat can be spent in increasing the temperature of the gas. In Fig. 110 B we have the same quantity of gas in a vessel, the volume of which is constant. In this case all the heat which is supplied to the gas will increase its temperature since no external work is done. It is obvious, therefore, that a greater quantity of heat will be necessary to raise the temperature of unit mass of a gas in the former case than in the latter, or, in other words, the specific heat of a gas at constant pressure is greater than its specific heat at constant volume.

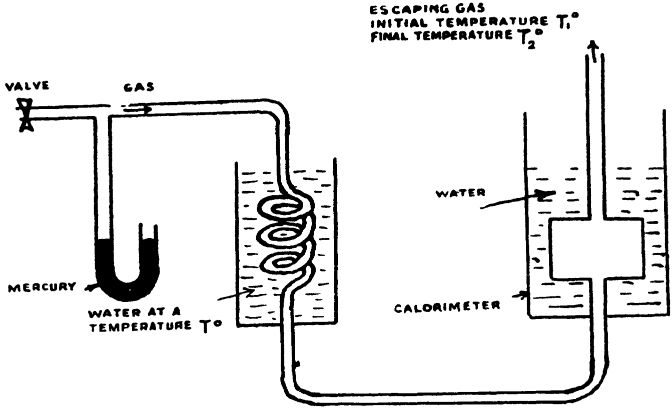


FIG. 111.

Fig. 111 shows the type of apparatus which could be used in order to determine the specific heat of a gas at constant pressure.

The gas enters the apparatus by means of the valve, as shown, and the pressure will be constant when the mercury stands at the same level in the two arms of the U-tube. A coil through which the gas passes is placed in a quantity of water at a known temperature T°. The initial temperature of the gas as it escapes is, say, $T_1°$, and its final temperature is $T_2°$, so that we must take the average temperature $\frac{T_1+T_2}{2}$.

If M=mass of gas used, S=its required specific heat, M_1=mass of water in the calorimeter, and w=water equivalent of the apparatus, then we have heat lost by the gas $=MS\left(T-\frac{T_1+T_2}{2}\right)$; heat gained by the water and the apparatus$=(M_1+w)(T_2-T_1)$. We therefore have

$$MS\left(T-\frac{T_1+T_2}{2}\right)=(M_1+w)(T_2-T_1),$$

from which we can find the required specific heat S.

Latent Heat

Two conditions are necessary in order to change a substance from the solid to the liquid state. The first condition is that the temperature of the solid must be at the melting-point, and the second condition is that the quantity of heat supplied must be proportional to the amount of the solid to be melted. It may be mentioned, however, that under artificial conditions it is sometimes possible to cool a liquid to a temperature below its freezing-point without actually freezing, provided that the liquid is not agitated in any way, is cooled uniformly and slowly, and is not in contact with its own solid. If even the smallest particle of the frozen solid is in the liquid, it will act as a nucleus from which freezing would rapidly spread.

The amount of heat taken in or given out by unit mass of a substance causing a change in state but not causing a change in temperature is known as the *latent heat* of the substance. For example, the latent heat of fusion of ice is the amount of heat required to turn unit mass of ice at the freezing-point of water into water at the same temperature. We define latent heat of vaporisation as the amount of heat required to turn unit mass of water at the boiling-point into steam at the same temperature. Our next consideration is the experimental determination of these two quantities.

In order to determine the latent heat of fusion of ice we use the apparatus as shown at B (Fig. 109), but instead of placing a known mass of metal in the water we place a known mass of ice. Suppose M=mass of ice used in the experiment and L=latent heat of ice, *i.e.*, 1 grm. of ice at 0° C. in turning to water at the same temperature requires L heat units. Let

M_1=mass of water in the calorimeter and w=water equivalent of the vessel. If the initial temperature of the water and calorimeter is T_1° C., it will drop to a temperature T_2° C. when all the ice has melted. Now by definition 1 grm. of ice at 0° C. in turning to water also at 0° C. requires L heat units, so that M grm. of ice at 0° C. in turning to water at 0° C. will require ML heat units. When all the ice has melted we shall then have M grm. of water at 0° C., which will be raised to the final temperature of the water in the calorimeter, viz., T_2° C. We can therefore state that the heat taken in by the ice causing it to melt and to be raised to a final temperature T_2° C.=heat given out by the water and calorimeter in cooling from T_1° to T_2° C. Our required equation to determine the unknown quantity L is therefore

$$ML+M(T_2-0)=(M_1+w)(T_1-T_2).$$

EXPERIMENT 29. *Determine the Latent Heat of Fusion of Ice from the following Data*—

Weight of copper calorimeter=58·9 grm.
(Water equivalent of calorimeter=5·8 grm.)
Weight of calorimeter+water=125·4 grm.
Initial temperature of water in calorimeter=21° C.

When all the ice had melted the temperature of the water was 11° C.

After the experiment weight of calorimeter+water+melted ice=132·4 grm.

What value does this experiment give for the latent heat of fusion of ice?

The latent heat of steam may be determined by means of the apparatus shown in Fig. 112. Steam is generated in the vessel A, and is allowed to pass along the bent glass tubing C and to condense into a known quantity of water contained in a calorimeter B.

The calorimeter is weighed empty, and when it is about one-third filled with water and, finally, when sufficient steam has condensed it is weighed again. From these particulars we can determine the quantity of water in the vessel and the amount of steam condensed.

Suppose we have M grm. of steam at the boiling-point, say 100° C., and that this quantity of steam condenses into M_1 grm. of water at a temperature T_1° C. If the temperature of the water rises to T_2° C., this will also be the final temperature of the condensed steam. Let w=water equivalent of the calorimeter. By definition 1 grm. of steam at the boiling-point of water gives out L heat units in condensing to water also at the boiling-point, so that M grm. of steam will give out ML heat units. Also in cooling from 100° C. to a temperature T_2° C. it will give out a further $M(100-T_2)$ heat units, and this total loss of heat will go to the calorimeter and the water it contains, *i.e.*, the heat taken in by the water and calorimeter will be $(M_1+w)(T_2-T_1)$. Our equation to determine L is therefore $ML+M(100-T_2)=(M_1+w)(T_2-T_1)$.

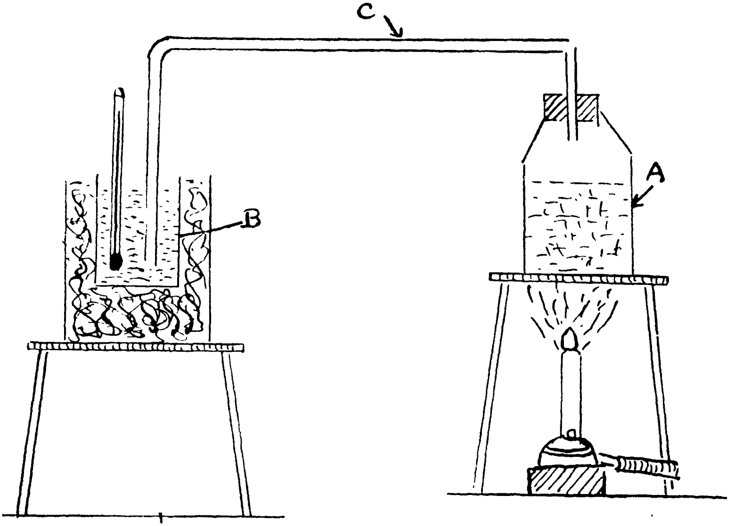


FIG. 112.

EXPERIMENT 30. *Determine the Latent Heat of Steam from the following Data—*

Weight of copper calorimeter=23·2 grm.
Weight of copper calorimeter+water=157·5 grm.
Weight of copper calorimeter+water+condensed steam =165·9 grm.

Initial temperature of steam$=100°$ C.
Initial temperature of water in calorimeter$=17°$ C.
Final temperature of water and steam$=53°$ C.
Specific heat of copper$=0{\cdot}1$.

What value do these readings give for the latent heat of steam ?

NOTE.—The readings for this experiment were obtained at normal atmospheric pressure, *i.e.*, when the height of the mercury barometer was 76 cm., and at this pressure the boiling-point of water$=100°$ C.

If possible the student should perform this experiment at atmospheric pressures above and below normal when, of course, the boiling-point of water will be above or below 100° C., and he should notice the effect on the value of the latent heat of steam.

Before leaving the subject of latent heat there are one or two cases of special interest to the engineer which we have to consider, because, as you know, the engineer has to deal with steam which may be formed under varying conditions. For example, steam formed under the conditions of Experiment 30 is known as dry saturated steam. The *total heat* of steam at any particular pressure is defined as the amount of heat which must be given to unit mass of water at the freezing-point in order to convert it into steam at the boiling-point, and it is denoted by H. In order to do this the temperature of the water must first be raised from the freezing-point to the boiling-point, and the heat necessary is called *sensible heat*, which is denoted by h. The heat required to turn unit mass of water at the boiling-point to steam at the same temperature is, of course, the latent heat L, so that for dry saturated steam the total heat H will be given by the relation $H=h+L$.

Sometimes steam, instead of being dry and saturated, may be wet. For example, in 1 lb. of wet steam there may be Q lb. of steam and $(1-Q)$ lb. of water, the quantity Q being known as the *dryness fraction* of the steam. In such a case the total heat will be given by the relation $H=h+QL$.

Again, if steam has been formed at a temperature T° C. and it continues to receive a supply of heat, its temperature and volume will increase, and the steam is said to be superheated. Let $T_S°$=superheat temperature, C_P=mean specific heat of superheated steam for a range in temperature T° to

$T_S°$, then the superheat S will be given by the relation $S=C_P(T_S°-T°)$, and the total heat of superheated steam will be $H=h+L+S$.

Example 2.—Steam is generated in a boiler at an absolute pressure of 180 lbs. per sq. in. from feed water which is at a temperature of 75° C. Determine the heat of formation per pound of steam from the feed water temperature, the dryness fraction of the steam being 0·8.

From Callendar's Steam Tables we find that at an absolute pressure of 180 lbs. per sq. in. the boiling-point of water =189·48° C., and the latent heat of steam=476·26 C.H.U.

Since the temperature of the feed water is 75° C. the sensible heat required will be (189·48—75)=114·48 C.H.U.

Therefore, using the formula $H=h+QL$, we have

$$\begin{aligned} H&=114{\cdot}48+0{\cdot}8(476{\cdot}26)\\ &=114{\cdot}48+381{\cdot}024=495{\cdot}504 \text{ C.H.U.}\end{aligned}$$

We often hear the engineer speak of the "calorific value" of a sample of fuel, by which he means the quantity of heat 1 lb. of the fuel will give out when completely burned. Fuels vary in quality, depending on the amount of hydrogen and carbon they contain. Fuels containing high percentages of these two elements will have a higher calorific value than those in which the percentage is low. The best Welsh coal, known as anthracite, has a high percentage of hydrogen, and the average heating value of this coal is about 16,500 B.Th.U. per lb., whereas the heating value of coals from other districts varies from about 12,000 to 14,500 B.Th.U. per lb. Oil fuels have a higher heating value than solid fuels, the average value being between 19,000 and 20,000 B.Th.U. per lb. An average heating value for coal gas is about 450 B.Th.U. per cub. ft.

We now have to consider experimental methods of determining the calorific value of fuels. In the case of coal we use the Lewis Thompson coal calorimeter, an illustration of which is given in Fig. 113.

The method of using the apparatus is as follows :—

A sample of coal is taken and powdered up very finely. A small quantity of the sample is then mixed with a special oxygen mixture which merely assists combustion and in no way adds to the heating value of the coal. This mixture is placed in the copper cylinder shown, and a fuse is inserted at the top. The cylinder is placed on the base and held in position by spring clips. The fuse is lighted and the hood (with tap closed) is placed over the cylinder and also held in position by the spring clips. The whole is then placed in a known quantity of water at a known temperature. As soon as combustion commences, bubbles of gas will be given off through the holes in the bottom of the hood, and when combustion ceases the tap is opened so that the water rushes in and abstracts the heat which has been evolved. This heat increases the temperature of the water, so that knowing the quantity of water and water equivalent of the vessel, the increase in temperature, and the amount of coal burnt, we can determine the calorific value.

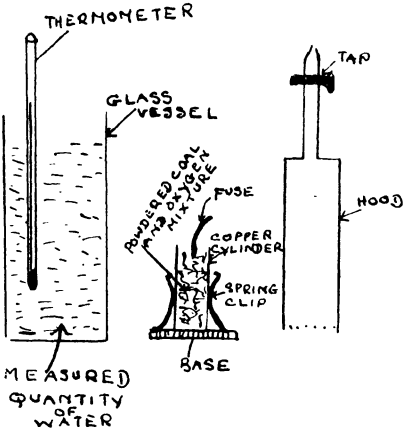


FIG. 113.

Let w lbs. = quantity of coal burnt, W = weight of water (pounds) in the vessel, and e = water equivalent of vessel. If $T_1°$ F. = initial temperature of water and $T_2°$ F. = final temperature, we have heat given out by w lbs. of coal $=(W+e)(T_2-T_1)$, *i.e.*, heating value of coal in British Thermal Units per pound $=\dfrac{(W+e)(T_2-T_1)}{w}$.

EXPERIMENT 31. *Determine the Heating Value of a Sample of Coal in British Thermal Units per Pound from the following Data obtained with the Apparatus shown in Fig.* 113.—

Weight of coal burnt$=2$ grm.
Quantity of water in glass vessel$=1{,}934$ c.c.
Initial temperature of water$=61°$ F. Final temperature $=74°$ F.
Water equivalent of the apparatus$=0{\cdot}125$ lb.

NOTE.— $$2 \text{ grm.}=\frac{2}{454}=0{\cdot}004404 \text{ lb.}$$

$$1934 \text{ c.c.}=1934 \text{ grm.}=\frac{1934}{454}=4{\cdot}26 \text{ lbs.}$$

A sketch of the Simmance-Abady gas calorimeter which we use to determine the heating value of coal-gas is given in Fig. 114.

Water enters the calorimeter A from the supply pipe, as shown, and after circulating round a number of coils in A finally leaves by the pipe B. In order to ensure complete circulation of the water the head of water in the tube C should be kept constant. The inlet thermometer D registers the temperature of the water as it enters, and the outlet thermometer E registers the temperature of the water as it leaves the calorimeter, the water being directed into a measuring vessel G when the thermometers D and E show a steady difference in temperature due to the heat received from the Bunsen burner placed as shown. The gas meter shown in the sketch registers the quantity of gas burnt in cubic feet, while a known quantity of water is collected in the vessel G.

Suppose the inlet thermometer registers $T_1°$ F. and the outlet thermometer reads $T_2°$ F., the quantity of water collected in G being M lbs. If w cub. ft. of gas are burnt while this quantity of water is being collected, then the calorific value of the coal-gas in British Thermal Units per cubic foot will be $\frac{M(T_2-T_1)}{w}$.

EXPERIMENT 32. *To Determine the Calorific Value of Coal-gas.*—The following readings were taken with an apparatus, as shown in Fig. 114.

Inlet temperature of water=62° F. Outlet temperature=76° F. Water collected in measuring vessel G while $\frac{1}{30}$ cub. ft. of gas was burnt=450 c.c. Determine the heating value of the gas in British Thermal Units per cubic foot, and in Centigrade Heat Units per cubic foot.

The apparatus shown in Fig. 114 may also be used in order to determine the heating value of a liquid fuel, but the Bunsen burner is removed and its place is taken by a lamp burning the oil under test.

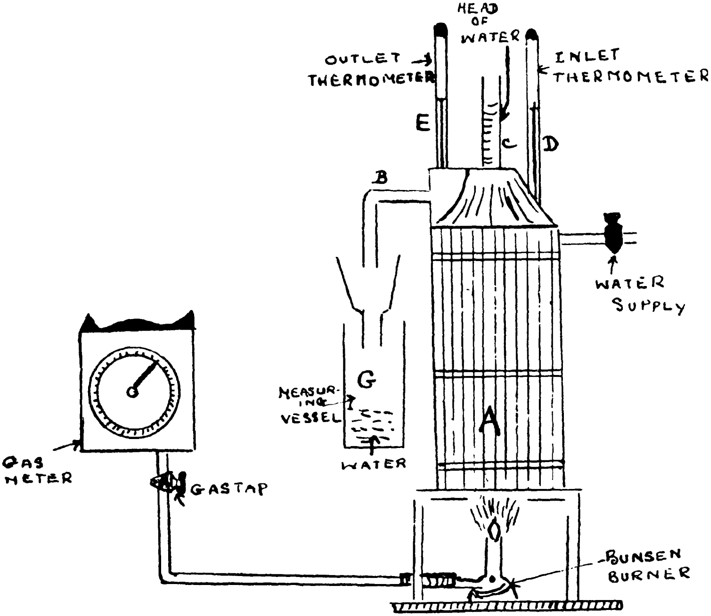


FIG. 114.

As in Experiment 32 a steady difference in temperature, as indicated on the inlet and outlet thermometers, is obtained by placing the lamp under A. When the temperature difference is constant the lamp containing the oil is balanced on a special balance supplied by the makers of the apparatus, the scale pan of the balance containing the lamp being placed under A. A known weight, say $\frac{1}{2}$ grm., is then added to the scale pan containing the lamp, and while the $\frac{1}{2}$ grm. of oil is being burnt, water is collected in the measuring vessel G. Knowing the quantity of oil burnt, the quantity of water in the measuring vessel, and the difference between the inlet and outlet temperatures, we can determine the calorific value of the oil.

MECHANICAL EQUIVALENT OF HEAT

It was stated in Chapter IX. that heat is a form of energy, and we must now consider this statement in greater detail.

The experiments Joule performed in Manchester between 1840 and 1850 enabled him to conclude that heat was produced at the expense of work, and finally he stated that the ratio $\frac{\text{work done}}{\text{heat produced}}$ was a constant quantity which is customarily denoted by J. This constant is known as the Mechanical Equivalent of Heat, the average of a number of values given by Joule with the apparatus he used being 773·37 ft.-lbs. per B.Th.U. The value of J as obtained with more elaborate apparatus is now given as 778 ft.-lbs. per B.Th.U., and the statement means that 1 B.Th.U. will be produced for every 778 ft.-lbs. of work performed. It will also be useful to remember that the value of J may be given as, roughly, 1,400 ft.-lbs. per C.H.U., or as $4{\cdot}2 \times 10^7$ ergs per calorie.

If W=work done and H=heat produced, we can write $W=JH$, which result is known as the First Law of Thermodynamics. We can express this law in words by saying that heat and work are mutually convertible, and that every unit of work performed produces a definite quantity of heat. This law is of the utmost importance and is the foundation on which the study of heat engines is built up.

Fig. 115 is a diagrammatic representation of Professor Callendar's apparatus, which may be used in order to determine the value of the mechanical equivalent of heat.

The hollow brake drum A is encircled one and a half times by a silk belt brake, three-quarters of the circumference being overlaid by the single part of the belt and the same amount by the double part. From the single part of the belt a weight carrier B is fixed on which small weights are placed. A spring balance, which acts against the small weights, is attached to the lower end of B, the other end being fixed to the frame of the apparatus. A weight carrier D is suspended from the double part of the belt, and on this are placed heavy weights. The drum is rotated by a wheel on the shaft through a coupling disc C, which is attached to the drum by insulating studs which prevent conduction of heat along the shaft. If the experiment is carried out at atmospheric temperature no correction for cooling need be applied. When the drum is rotated the small weights are adjusted so that the heavy weights are lifted clear of the stops, and the pointer on the spring balance should be near the centre of its scale. A known quantity of water is placed in the drum and a bent thermometer is inserted, as shown, so that the increase in temperature of the water may be noted.

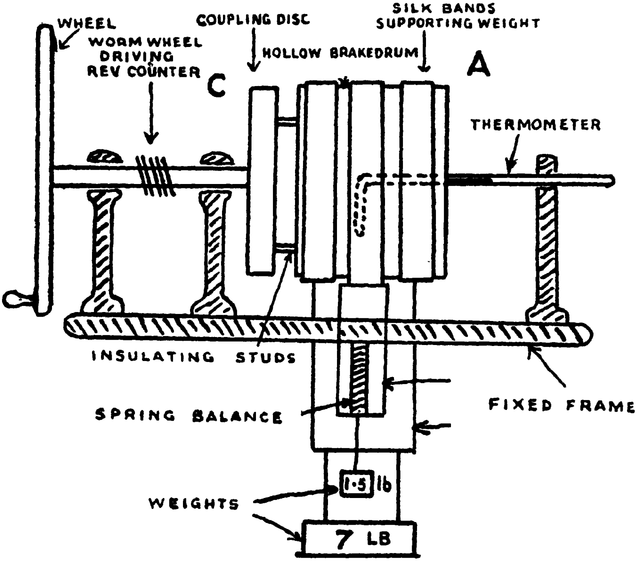


FIG. 115.

In using the apparatus to determine the value of J we require the following particulars :—

Heavy weight hung on to the carrier at the double end of the silk belt=W lbs., weight hung on to the carrier at the other end of the belt=w lbs., spring balance reading=S lbs., diameter of drum=d ft., revolutions as shown by revolution counter=N, mass of water in the drum=M lbs., water equivalent of drum=m lbs. Water changes in temperature from T_1° to T_2° F., or these may be expressed on the Centigrade scale.

Circumference of drum=πd, and force in pounds acting at the circumference=$(W+S-w)$, so that the total work done in N revs. will be $(W+S-w)\pi dN$ ft.-lbs.

Heat produced by this work=$(M+m)(T_2-T_1)$ heat units or $(M+m)(T_2-T_1)J$ ft.-lbs. We therefore determine the value of J from the relation $J=\frac{(W+S-w)\pi dN}{(M+m)(T_2-T_1)}$.

EXPERIMENT 33. *Determine the Value of J by means of Callendar's Apparatus.*—By the method explained above determine the numerical value of J in foot-pounds per centigrade heat units from the following data :—

Heavy weight hung on the weight carrier, 7 lbs.

Weight on the other weight carrier=0·5 lb., spring balance reading=1 lb., diameter of drum =0·5 ft., mass of water=1 lb., water equivalent =0·1 lb. After 100 revs. of the drum the temperature of the water rose from 15·25° to 16° C.

Neglect cooling and radiation losses.

The relation between the specific heat of a gas at constant pressure, constant volume, and the mechanical equivalent of heat.

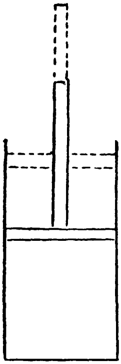


FIG. 116.

Fig. 116 represents a cylinder fitted with a smooth piston and containing a quantity of gas. Let A=area of piston, P=atmospheric pressure, T_1°=initial temperature of the gas, and T_2°=its final temperature. V_0=volume of the gas at 0° C., and C=coefficient of cubic expansion of the gas.

Work done in raising the piston through a distance d=force×distance=PAd, and this is equal to P×the increase in volume. But at T_1° C. the volume of the gas $V_1=V_0(1+CT_1)$ and at T_2° the volume $V_2=V_0(1+CT_2)$ so that the change in volume $V_2-V_1=V_0C(T_2-T_1)$. We can therefore say that the work done=$PV_0C(T_2-T_1)$.

Now let m=mass of the gas, C_P=its specific heat at constant pressure, C_V=its specific heat at constant volume, and D=density of the gas at 0° C. We can now state that the difference in heat units required to raise the temperature of the gas from $T_1°$ to $T_2° = m(C_P - C_V)(T_2 - T_1)$, and if J=mechanical equivalent of heat we can write

$$Jm(C_P - C_V)(T_2 - T_1) = PV_0C(T_2 - T_1),$$

or

$$J = \frac{V_0}{m}\left(\frac{PC}{C_P - C_V}\right).$$

But $D = \frac{m}{V_0}$, so that finally we have

$$J = \frac{PC}{D(C_P - C_V)}.$$

Example 3.—Determine the speed with which a lead bullet at 35° C. must strike an obstacle in order that the heat produced when its motion is stopped, assuming all the heat to be in the bullet itself, may be just sufficient to melt it.

Specific heat of lead=0·03, melting point of lead=335° C., latent heat of fusion of lead=5·37, mechanical equivalent of heat=1,400 ft.-lbs. per C.H.U.

If m=mass of the bullet in pounds and V=its speed in feet per second, then the kinetic energy just before it strikes the obstacle $= \frac{1}{2}\frac{mV^2}{g}$ ft.-lbs. $= \frac{mV^2}{64}$ ft.-lbs., or $\frac{mV^2}{64 \times 1400}$ heat units.

Heat required to raise the temperature of the bullet to its melting point=mass × specific heat × change in temperature $= m \times 0{\cdot}03 \times 300$ units.

Heat required to melt the bullet=mass × latent heat $= m \times 5{\cdot}37$ units.

Therefore since work done=heat produced, both being in the same units, we have

$$\frac{mV^2}{64 \times 1400} = (m \times 0{\cdot}03 \times 300) + (m \times 5{\cdot}37),$$

or, since m is constant,

$$\frac{V^2}{64 \times 1400} = (0{\cdot}03 \times 300) + (5{\cdot}37).$$

Therefore $$V^2 = 14{\cdot}37 \times 64 \times 1400,$$

or $$V = \sqrt{14{\cdot}37 \times 64 \times 1400} = 1134 \text{ ft. per sec.}$$

HEAT TRANSMISSION

Heat may be transmitted from one point to another in three different ways, viz., by *radiation*, by *convection*, or by *conduction*, and we shall now consider each of these methods in turn.

By radiation we mean the transmission of heat through the ether or space by rays of radiant energy which become converted into heat when absorbed by matter. The medium through which radiant energy passes is not heated, and substances such as air which transmit radiant heat but which do not receive heat themselves are known as *diathermanous substances*. *Adiathermanous* is the name given to substances which receive heat by radiation.

Most bodies will absorb radiant energy, but the amount absorbed will, of course, depend on the nature of the substance. Good absorbers of heat are good radiators and vice versa. The ratio $\frac{\text{energy absorbed by a body}}{\text{total energy falling on the body}}$ is known as the *absorptive power*. We define *emissivity* as the amount of energy radiated per unit area per unit time per unit difference in temperature.

All types of radiation, heat, light, electricity, etc., are due to wave motions in the ether or space, but whereas in the case of light radiation the wave-length is very short, that in the case of heat radiations is very long.

The diagram shown in Fig. 117 represents, roughly, our range in wave motion. On the left of the diagram we have the electric waves, such as those used in wireless, and the wave-length of these rays is very long, but the wave-length decreases as we travel along the diagram from left to right. All heated bodies emit radiations of long wave-length, but much shorter than wireless waves, and these radiations belong to what is known as the infra-red end of the spectrum. If the temperature of the body is raised to about 500° C. the wave-length is so short that it produces the sensation called sight, and we are then able to see the red end of the visible spectrum. A further supply of heat causing the temperature to rise to about 1,250° C. will bring us through the other colours, shown in Fig. 117, to the violet end of the spectrum, and at a temperature of about 1,350° C. we come to the ultra-violet rays which are invisible but which cause chemical action in a photographic film. Finally, on the extreme right of the diagram, we have the Röntgen or X-rays, the wavelength of which is so short as to enable the rays to penetrate substances which are opaque to ordinary light. These rays are useful to the engineer in that they may be used to detect flaws in pieces of metal.

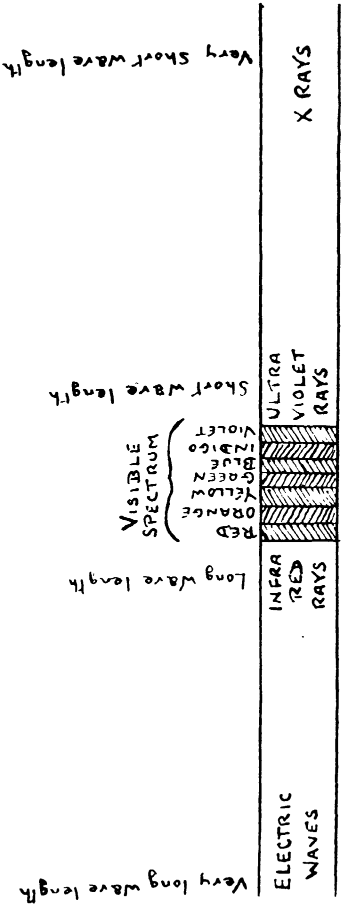


FIG. 117.

Prevost's "Theory of Exchanges" states that any substance not at the absolute zero of temperature will emit radiations, and will continue to do so until a state of thermal equilibrium is reached, which will be when the energy radiated per unit time from one substance is equal to the energy absorbed in the form of radiations by surrounding substances. This means that radiation will continue so long as there is a difference in temperature between the bodies concerned.

EXPERIMENT 34. *To Compare the Radiations Emitted by a Bright and a Dull Surface.*—Obtain a brass or other metal plate about 1 ft. square, polish one side, and paint the other side with lamp black. Place the sheet of metal over a source of heat, and leave it there for about one minute. Hold the metal with a non-conducting material about 2 ft. from your face, having the polished side towards you. Notice the heat received by radiation. Now turn the dull side towards you, keeping it at the same distance, and notice the marked difference in the heat radiated. What would you conclude from this simple experiment?

By convection we mean the transmission of heat by the actual transference of heated matter in the substance. This method is applied to liquids and gases, the heat being supplied below the substance. Particles nearest the supply of heat will be warmed, and becoming less dense will move upwards from the heat supply. The colder and denser particles will then fall and take the places vacated by the lighter particles. These in turn will receive heat, become less dense, and rise in the liquid or gas, and so the circulation continues, the whole mass ultimately becoming heated by convection currents.

Natural ventilating systems depend for their action on convection currents set up in the air inside a heated room. Also, in a hot-water supply system in a house convection currents are set up in the water by the heat of the kitchen fire.

In conduction heat is transferred by an actual flow of heat from the hotter body to a cooler one in contact with it, or from the hotter to the colder parts of a continuous body.

Metals are good heat conductors, but substances such as wood, felt, etc., liquids, and gases are very poor in this respect. Other substances such as brick, stone, slate, etc., occupy an intermediate position, but are classified as very poor compared with metals.

If we apply a light to coal-gas issuing from a jet, the temperature of the gas will be raised above its temperature of ignition and the gas will, of course, burn. If we now place a piece of wire gauze above the flame, the gas will burn between the jet and the gauze, but it can be arranged that it will not burn above the gauze. Also, if we apply a light to the gas above the gauze it can be made to burn there but not between the gauze and the jet. The reason for this (A, Fig. 118) is that the wire gauze is a good heat conductor, and heat is conducted away from that part of the flame in contact with it sufficiently to lower the temperature of the gas below its ignition point so that it will not burn.

This principle is utilised in the Davy safety-lamp which is used in coal-mines (B, Fig. 118). When dangerous gases are present they will pass through the gauze of the lamp and burn inside the lamp by the flame from a candle. As soon as the dangerous gases are detected by the miner he warns other workers so that they may leave the danger spot and the mine can be thoroughly ventilated.

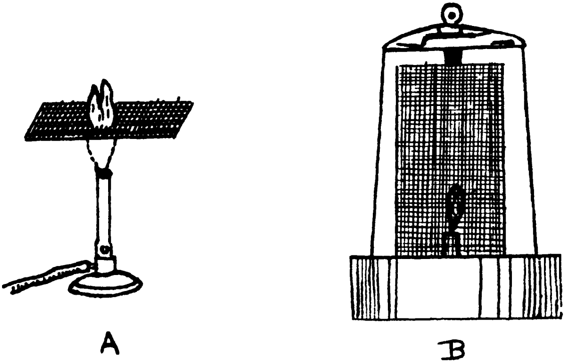


Fig. 118.

Fig. 119 shows a rectangular piece of metal, the area of one face being A sq. cm., the thickness of the plate being *d* cm.; $T_1°$ C. is the temperature on one side of the plate and $T_2°$ C. is the temperature on the opposite side. If $T_1°$ C. is a higher temperature than $T_2°$ C. there will be a flow of heat through the plate from left to right, and the quantity of heat passing through will depend on the area of the plate, its thickness, the difference in temperature between the two faces, and the time during which the heat is allowed to flow.

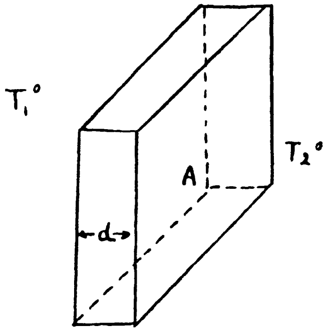


Fig. 119.

Referring to Fig. 119, the ratio

$$\frac{\text{Difference in temperature between the two sides}}{\text{Thickness of plate}},$$

i.e., $$\frac{T_1-T_2}{d},$$

is called the temperature gradient. The heat passing through the plate will be directly proportional to the area A, directly proportional to (T_1-T_2), directly proportional to the time during which the heat flows t secs., and inversely proportional to the thickness of the plate d, *i.e.*, if Q=quantity of heat passing $Q \propto \frac{A(T_1-T_2)t}{d}$, or we can write $Q=K\frac{A(T_1-T_2)t}{d}$, in which the constant K is called the thermal conductivity of the metal. In words the conductivity may be defined as the quantity of heat transferred per second per unit area for a temperature gradient of 1° C. per centimetre.

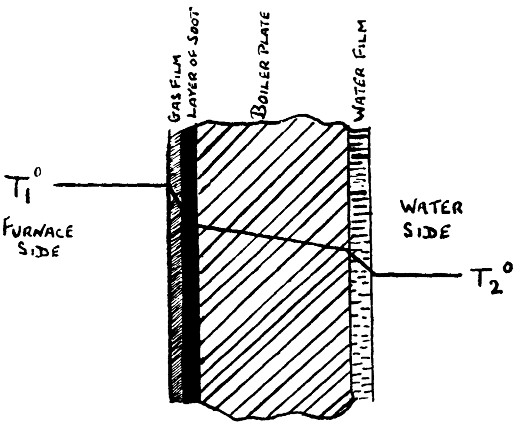


Fig. 120.

The water in a steam boiler which is used for generating steam is heated by convection currents which are set up by the heat from the furnace which is conducted through the boiler plate. Although the metal of which the boiler is constructed is a good conductor of heat, there is a considerable drop in temperature between the furnace side of the metal plate and the water side. We will assume the temperature difference to be $T_1^\circ - T_2^\circ$, as illustrated in Fig. 120. The reason for this marked drop in temperature is that a deposit of soot and other products of combustion forms on the furnace side of the plate, and next to this soot deposit it has been proved that there is a very thin gas film. As both these substances are very poor heat conductors the furnace side of the plate must be at a temperature well below T_1°. Again, on the water side there is always a stationary water film present, which also accounts for a large drop in temperature. In Fig. 120 the slope of the lines represents, roughly, the temperature gradient for the substances, as indicated, and it will be noticed that the temperature gradient for the boiler plate itself is less than that of the substances which are deposited on the plate.

Example 4.—Determine the amount of heat which will be transmitted in 10 mins. through a square steel plate of 100 cm. side and 5 cm. thick. The temperature on one side is 15° C. and that on the opposite side is 25° C. Conductivity of steel$=0{\cdot}158$.

Using the formula $Q=K\frac{A(T_1-T_2)t}{d}$, and substituting the given values, we have

$$Q=\frac{0{\cdot}158\times10000\times10\times600}{5}=1896000 \text{ calories.}$$

NINTH SET OF EXAMPLES

1. Engineers speak of sensible heat, latent heat, and total heat of steam. What do you understand by these expressions? Describe how you would obtain the value of the latent heat of steam at atmospheric pressure and state what result you would expect to obtain. U.L.C.I.

2. What is meant by the terms " capacity for heat " and " specific heat " ? It is found that 31 B.Th.U. are required to raise the temperature of 1 lb. of lead through 1,000° F. What is the specific heat of lead ? U.L.C.I.

3. A certain coal is advertised as having a calorific value

of 14,000 B.Th.U. per lb. Explain fully what this means, and explain how if you purchased some of this coal you could check the truth of the statement. U.L.C.I.

4. What conditions are necessary for the change of a substance from the solid to the liquid state? What is meant by the freezing-point of a substance? When a liquid is cooled does it always begin to solidify when its temperature reaches the freezing-point? L.M.

5. Define specific heat. One hundred grammes of copper of specific heat 0·1 are cooled to —50° C. and then immersed in ice-cold water. Calculate the amount of ice formed. (Latent heat of fusion of ice=80.) L.M.

6. A copper vessel weighs 20 grm. and contains 20 grm. of a substance which melts at 59° C. and which has a specific heat of 0·75 when liquid and 0·32 when solid. If the latent heat of the substance is 94 calories per grm., calculate the heat lost by the vessel and its contents in cooling from 100° to 40° C. (Specific heat of copper=0·1.)

7. Define "saturated steam," "superheated steam," and "dryness fraction of steam."

Steam is generated in a boiler at a pressure of 160 lbs. per sq. in. absolute from feed water at 120° F. Determine the heat of formation of steam per pound from the feed-water temperature, assuming a dryness fraction of 0·9.

(From steam tables we notice that at a pressure of 160 lbs. per sq. in. absolute the boiling-point=363·48° F., and the latent heat of steam=865·09 B.Th.U.)

8. What is meant by the statement that heat is a form of energy? Mention some other forms of energy. Two balls of equal weight, one of indiarubber and the other of soft clay, are dropped on to a hard floor from the same height. In the case of which would you expect the greater heat to be developed by impact on the floor? Give reasons. L.M.

9. An open copper vessel contains 1,000 c.c. of water at 85° C. and it is placed upon a stone bench. Describe the different ways in which the vessel and the water lose heat. How would you reduce the heat losses to a minimum?

10. Sketch in outline and briefly describe any calorimeter with which you are familiar for determining the calorific value of a fuel.

Determine the calorific value of coal when 1 grm. of it burnt in a calorimeter caused a rise of temperature of 3·52° C.

in 2,000 grm. of water, the water equivalent of the calorimeter being 475 grm. U.L.C.I.

11. Explain the meaning of the expression "mechanical equivalent of heat." What is the numerical value of the mechanical equivalent of 1 unit of heat?

The horse-power of an engine is 30. How many foot-pounds of work per minute does this represent? Assuming this amount of work to be converted into heat by a friction brake, find how many heat units will be generated.

U.L.C.I.

12. How many heat units are required to generate 1,000 lbs. of dry saturated steam at an absolute pressure of 175 lbs. per sq. in. from feed water at 12° C.? What would be the "total heat" of 1 lb. of steam at the above pressure?

The following data are abstracted from a steam table :—

Pressure.	Temperature.	Sensible Heat per Pound.	Latent Heat per Pound.
Lbs. per Sq. In.	° C.	Cent. Heat Units.	Cent. Heat Units.
175	188·2	190·9	477·3

U.L.C.I.

13. A piece of platinum weighing 150 grm. is taken from a furnace and dropped into 98 grm. of water at 12° C. contained in a copper vessel weighing 20 grm. If the temperature of the water rose to 40° C., what was the temperature of the furnace? (Specific heats : Platinum$=0{\cdot}032$, copper$=0{\cdot}1$.)

14. Explain why the specific heat of a gas at constant pressure is greater than its specific heat at constant volume.

Knowing the two specific heats of air and also its density at a given pressure and temperature obtain an expression for the mechanical equivalent of heat.

15. Define thermal conductivity.

In a certain time it was found that 18,000,000 heat units passed through a rectangular plate of copper 100 cm. by 100 cm. by 5 cm., and the difference in temperature between the two sides was 10° C. Assuming the conductivity of copper to be 1, calculate the time during which the heat was passing.

CHAPTER XI

A FEW ESSENTIAL FACTS RELATING TO COMBUSTION

An element is defined as any substance which cannot be split up by chemical means into parts possessing different chemical properties, such as, for example, hydrogen, oxygen, iron, copper, radium, etc. A number of elements may, however, be combined, and so form a substance which possesses properties entirely different from those of the elements forming it, such substances being known as compounds. For example, consider hydrogen and oxygen ; these are elements which possess definite properties, but when they are combined in the proportion of 2 : 1 they form the compound water, which, as you know, possesses very different properties.

Combustion is normally a vigorous chemical reaction which takes place between two substances accompanied by the production of considerable heat. For the success of this reaction we require (1) a combustible body, (2) a supporter of combustion (oxygen), and (3) a sufficiently high temperature. The engineer has to study problems in connection with the combustion of solid, liquid, and gaseous fuels, and as a foundation for this study it will be necessary to consider one or two elementary facts of chemistry.

A molecule is defined as the smallest particle of a substance which can have a separate existence and yet retain the properties of that substance. A molecule contains a large number of atoms, an atom being defined as the smallest part of an element which can take part in a chemical reaction. At this stage of our work the subdivision of the atom into electrons is of little interest to the would-be engineer.

Chemists represent 1 atom of an element by a symbol or a combination of symbols, such as, for example, H for hydrogen, C for carbon, Fe for iron (Latin, *ferrum*), etc., and when we find a suffix after the symbol, such as H_2, the suffix 2 would denote that there were 2 atoms of hydrogen. In order to represent a chemical compound we combine the symbols of the atoms which form 1 molecule of the compound. For example, it is stated above that hydrogen and oxygen in the proportion of 2 : 1 form water, so that this compound may be represented by H_2O. Further, if we wished to represent 2 molecules of water, we should write $2H_2O$.

The lightest known element is hydrogen, and it is usual to express the relative densities of all gases in terms of hydrogen as unity. The statement that the atomic weight of carbon is 12 simply means that an atom of carbon is twelve times as heavy as an atom of hydrogen. Also, we frequently require the molecular weight, *i.e.*, the weight of a molecule of a gas, and this is obtained by adding together the relative weights of all the atoms of which the molecule is composed. Consider carbon dioxide, CO_2. This contains 1 atom of carbon and 2 of oxygen. The atomic weight of carbon is 12 and that of oxygen 16, so that the molecular weight of CO_2 is $12+(2\times16)=44$.

The following table will be useful for solving problems on combustion :—

Substance.	Symbol.	Atomic Weight.	Molecular Weight.
Hydrogen	H	1	2
Oxygen	O	16	32
Water	H_2O	...	18
Carbon	C	12	...
Carbon monoxide . .	CO	...	28
Carbon dioxide . . .	CO_2	...	44
Nitrogen	N	14	28
Sulphur	S	32	64

In this work we are not in a position to study chemical laws and relationships experimentally, but the statements and conclusions given should be remembered.

As a result of his experiments the Italian physicist Avogadro stated what is known as Avogadro's Law, and subsequently, by mathematical reasoning, Maxwell came to the same conclusion. This law states that equal volumes of different gases when under the same conditions of temperature and pressure contain the same number of molecules, or expressing it in a slightly different way it means that 1 molecule of all gases will occupy the same volume.

From the chemist's point of view Avogadro's Law is of very great importance, but for the present it will be sufficient if the engineering student remembers it in the form as given above. At this stage, however, it may be advisable for the engineer to be able to use Avogadro's Law together with the definition of specific gravity or atomic weight of a gas in order to show that the molecular weight of a gas is twice the atomic weight, as given in the above table of molecular and atomic weights. The reasoning is as follows: Consider a certain volume of any gas and an equal volume of hydrogen, both gases being under the same conditions of pressure and temperature. Suppose there are N molecules of the gas in our fixed volume, then, according to the above-mentioned law, there will also be N molecules of hydrogen in the same volume of this gas. By definition we have specific gravity or atomic weight of a gas $= \frac{\text{weight of a certain volume of the gas}}{\text{weight of an equal volume of hydrogen}}$, and this ratio $= \frac{\text{weight of N molecules of the gas}}{\text{weight of N molecules of hydrogen}}$. Further, if we deal with 1 molecule only we can write atomic weight $= \frac{\text{weight of 1 molecule of the gas}}{\text{weight of 1 molecule of hydrogen}}$. The chemist has proved that 1 molecule of hydrogen contains 2 atoms, so that if we take the atom of hydrogen as our unit mass we can definitely state that the weight of 1 molecule of hydrogen will be 2. Therefore, finally, we have atomic weight of the gas $= \frac{\text{weight of 1 molecule of the gas}}{2}$, or, in other words, the molecular weight of a gas is twice the atomic weight. If, therefore, we obtain the atomic weight of a gas from tabulated values we can easily obtain the molecular weight when required.

CHEMICAL EQUATIONS

Provided that the conditions are suitable, chemical substances react on one another when brought together, and the reaction which takes place is represented by what we call a chemical equation. In these equations chemical symbols representing the substances involved in a reaction are suitably arranged, the state of affairs before and after the reaction being separated by the equality sign. For example, the equation $Zn+H_2SO_4=ZnSO_4+H_2$ represents the action of zinc on dilute sulphuric acid. It not only means that zinc added to sulphuric acid produces zinc sulphate and liberates hydrogen, but if we know the atomic weights it gives important information about the quantities required.

The following equations represent the combustion of certain substances with which the engineer should be familiar.

The combustion of hydrogen to form steam is represented by the equation $\underset{4+32=36}{2H_2+O_2=2H_2O}$, the numbers under this and the following equations representing the molecular weights of the constituents concerned. The equation means that 2 volumes of hydrogen combine with 1 volume of oxygen to form 2 volumes of steam. Dealing with the molecular weights the equation means that when 1 lb. of hydrogen burns to form steam it requires 8 lbs. of oxygen and produces 9 lbs. of steam. From this equation we can also state that since 8 parts by weight of oxygen are required to form steam with every 1 part by weight of hydrogen the amount of hydrogen available for heating purposes will be the actual amount of hydrogen present minus one-eighth of the quantity of oxygen. In dealing with the combustion of fuels this statement is very important and should be remembered. The importance of this statement is that the steam formed will abstract a large amount of heat from the hydrogen owing to the fact that steam has a large latent heat.

Carbon when completely burnt turns to carbon dioxide, the reaction being represented by the equation $\underset{12+32=44}{C+O_2=CO_2}$. From this equation it can be stated that when 1 lb. of carbon burns to carbon dioxide, $\frac{32}{12}$ or 2·66 lbs. of oxygen will be required and $\frac{44}{12}$ or 3·66 lbs. of carbon dioxide will be produced. If, however, the combustion is not complete, the carbon, instead of burning to carbon dioxide, CO_2, burns to carbon monoxide, CO, and as this reaction involves a large loss of heat the efficient stoker should see that his furnace always has a plentiful air supply. A thick layer of coal on the firebars is conducive to incomplete combustion, and in such a case the remedy is to admit air above the fire in order that the CO present may burn to CO_2.

The reaction which takes place during the combustion of sulphur is represented by the equation $\underset{32+32=64}{S+O_2=SO_2}$, and it means that when 1 lb. of sulphur burns to sulphur dioxide it will require 1 lb. of oxygen and will produce 2 lbs. of sulphur dioxide.

The chief constituents of solid fuels are carbon, hydrogen, oxygen, and sulphur, but as the presence of sulphur may be injurious and it does not contribute very largely to the heating value of the coal, for steam-raising purposes it will be an advantage to obtain a sample of coal in which the percentage of sulphur is low.

Minimum Amount of Air Required for Complete Combustion

From the above equations representing combustion we are now in a position to obtain an expression for the theoretical minimum quantity of air which will be necessary for the complete combustion of 1 lb. of a solid fuel.

Suppose 1 lb. of a fuel contains C lbs. of carbon, H lbs. of hydrogen, O lbs. of oxygen, and S lbs. of sulphur. We have seen above that 1 lb. of carbon requires 2·66 lbs. of oxygen in order that combustion may be complete. Also, 1 lb. of hydrogen will require 8 lbs. of oxygen, and that 1 lb. of sulphur requires 1 lb. of oxygen. The chemist has proved among other things that air contains 23 per cent. by weight of oxygen, or, in other words, 1 lb. of oxygen will be contained in $\frac{100}{23}$ or 4·35 lbs. of air. One pound of carbon will therefore require $2{\cdot}66\times4{\cdot}35$ or 11·6 lbs. of air, 1 lb. of hydrogen will require $8\times4{\cdot}35$ or 34·8 lbs. of air, and 1 lb. of sulphur will require $1\times4{\cdot}35$, *i.e.*, 4·35 lbs. of air. We can therefore finally state that for the complete combustion of 1 lb. of a fuel the quantity of air necessary in pounds will be given by the formula $11{\cdot}6C+34{\cdot}8H+4{\cdot}35S$.

Example 1.—A sample of coal contains 87 per cent. C, 5 per cent. H, 4 per cent. O, the remainder being ash. Determine the calorific value of the coal in British Thermal Units per pound, and the minimum quantity of air necessary for its complete combustion.

Heating values, British Thermal Units per pound: C, 14,000; H, 62,000.

Per cent. C present$=0{\cdot}87$, so that heating value of $C=14000\times0{\cdot}87=12180$. Per cent. H present$=0{\cdot}05$, per cent. oxygen$=0{\cdot}04$, so that the hydrogen available for heating purposes will be $0{\cdot}05-\frac{0{\cdot}04}{8}=0{\cdot}05-0{\cdot}005=0{\cdot}045$. Therefore heating value of $H=62000\times0{\cdot}045=2790$. Total heating value per pound is therefore $12180+2790=14970$ B.Th.U.

Minimum air required for complete combustion will be given by $11{\cdot}6\times0{\cdot}87+34{\cdot}8\times0{\cdot}05=10{\cdot}092+1{\cdot}74=11{\cdot}832$ lbs.

NOTE.—In practice 14 or 15 lbs. of air would be supplied per pound of coal in order to ensure complete combustion.

With this brief introduction to the study of combustion from the theoretical point of view we must now consider one or two practical details which are necessary in order that the efficiency of a furnace may be as high as possible.

The efficiency of a furnace is defined as the ratio $\frac{\text{actual heat supplied by the coal}}{\text{heating value of the coal used}}$, and for this ratio to be a maximum the first essential is to have a thin and uniform layer of coal spread over the whole grate. The next point to bear in mind, and it is a point which is very often overlooked, is that the furnace must be charged regularly and in a scientific manner. It is bad policy to allow a fire to burn too low before recharging, and when it has been charged the draught should always be regulated.

One method of charging a fire by hand is known as alternate side firing. In this method a charge is placed first on one side of the furnace, and when this side is giving out its maximum heat a fresh charge is placed on the opposite side, and the smoke formed by the new charge is then consumed by the side which is in a state of incandescence. This method of stoking maintains a fairly uniform temperature, and it is, of course, an advantage from a health point of view to have large volumes of smoke consumed rather than to have them sent forth into the atmosphere.

In the method of stoking known as spreading, a small charge is spread evenly over the whole of the grate surface. As in the previous case the temperature of the furnace is fairly uniform, but the chief disadvantage is that it is necessary to recharge the furnace at very frequent intervals.

Another method of firing is known as coking stoking, and this is the same in principle as that employed in mechanical stokers, which will be described shortly. In this method a charge is placed on the front of the fire-grate, and it is left until all the volatiles have been driven off. It is then pushed towards the back of the grate when the heat is still sufficiently great to consume the smoke which passes along after a fresh charge. The disadvantage of this method of firing when done by hand is that the fire has to be disturbed at frequent intervals.

The efficiency of furnaces of all types, both large and small, will be low unless the spaces between the fire-bars and the ash-pits are thoroughly cleaned regularly. Clinkers and all other products of combustion which adhere to the fire-bars should be removed, and in order to prevent their formation the use of steam or water under the grates has been proved very satisfactory. On the other hand, some engineers state that this causes excessive loss of heat at the chimney. There certainly will be some loss of heat at the chimney, and especially if the temperature of the flue gases is high, but to compensate for this loss we must take into account the saving of the time involved in removing the deposits from the bars, and also the fact that in preventing the formation of these deposits the life of the fire-grate will be prolonged.

The most economical size of fire-grate will, of course, depend on what work the furnace has to perform. For example, in order to determine the size of a grate for a steam boiler we must know the quantity of steam required, say, per hour, the rate at which combustion will take place, *i.e.*, so many pounds of coal per unit area per hour, and also the equivalent evaporation of the fuel used. The term " equivalent evaporation " means the quantity of water in pounds at the boiling-point which can be turned into steam at the same temperature by the heat contained in 1 lb. of the fuel, *i.e.*, it is another way of stating the heating value of a fuel.

Example 2.—A steam boiler is required to generate 24,000 lbs. of steam per hour, and the rate of combustion is 20 lbs. of coal per hour per square foot of heating surface. If the equivalent evaporation of the coal used is 12 lbs., determine the necessary grate area.

Steam required per hour=24,000 lbs.

Since 1 lb. of the coal will evaporate 12 lbs. of water, and 20 lbs. of coal are burnt per hour per square foot of surface, the required area of grate$=\frac{24000}{12\times 20}=100$ sq. ft.

A high efficiency and the economical working of a power plant cannot be maintained unless all the equipment of the plant is efficient also, and in this connection the first requirement is for those in authority to see that efficient and economical methods of combustion are adopted. In small steam plants it will be necessary to charge the furnace by hand, and the above-mentioned methods of hand-firing will in such cases give the best results, but even with the most conscientious and efficient stoker there will be unavoidable heat losses.

Mechanical Stokers

As already mentioned, the coking stoking method of firing is employed in mechanical stokers, and in power plants where they are used we have a much more efficient combustion of fuel and better working generally of boilers. In addition, the quantity of smoke sent into the atmosphere is considerably reduced. The fuel is contained in hoppers, and is fed on to a moving grate where the volatiles are driven off and consumed. It then passes through an area of vigorous combustion, and when this is complete it passes to the ash-pit. The supply of coal from the hoppers and the speed at which the grate travels can be regulated to suit any particular conditions of working.

One or two different types of boilers will be described in the next chapter, but it may be mentioned here that, power for power, the water-tube boiler is more efficient than the fire-tube type. When every one is preaching economy it would not be good policy to scrap a fire-tube boiler and replace it with a water-tube boiler, but in many cases it would aid in the economical working of a power plant to fit a mechanical stoker to the fire-tube boiler. The chief factor in the economical working of any power plant is efficient combustion of the fuel, and the mechanical stoker has been designed to bring about this result.

With the best quality coals we always find a large proportion of incombustible matter, and if this is shovelled into a furnace it is obviously wasteful both from the money and heat points of view. For some considerable time British and American engineers have been experimenting with pulverised fuel in boiler furnaces, but it is only since 1927 that engineers generally have been convinced that this method of firing gives the most economical results. The student will now realise that in order to derive as much heat as possible from burning coal it is essential to let every particle of the fuel have sufficient air for its complete combustion and that this can only be done successfully when the coal is pulverised and admitted to the furnace in powder form.

For steam-raising purposes coals are classified according to size, heating value, volatiles, caking characteristics, etc., all of which are very important factors in connection with the efficiency of a furnace. For example, in an electric generating station, where the load is constantly fluctuating, the result of using low quality coal would only mean lower efficiency and a lower steaming capacity of the boilers. On the other hand, with pulverised fuel firing it is possible to consume efficiently almost any grade of coal, and in most cases, from an economic point of view, this would be the only sound proposition.

The pulverised fuel and air, the latter being heated to about 600° F., are admitted together from opposite corners of the combustion chamber, and meeting at the centre create what is known as turbulence. It has been proved that the greater the turbulence the more rapid and complete will be the combustion of the combustible particles and gases. In addition, all volatile constituents of the fuel are consumed almost as soon as they enter the combustion chamber, so that as there is no sudden cooling of partially consumed hydrocarbons there will be no deposit of carbon in the form of soot, the absence of which means higher efficiency of the steam plant.

The steam engineer realises that it is essential to maintain a high efficiency of his plant over a prolonged period and under various conditions of load, and according to reports from various authorities the pulverised fuel method of firing will bring about this state of affairs. If for any reason a boiler is not needed, the fire is turned out and may be restarted at short notice, and even a cold boiler can be brought into full steaming capacity in less than a quarter of an hour. The plant is not restricted to a particular quality of coal because the pulverising equipment can handle and the furnace can consume many varieties.

It was mentioned above that the air supplied with the pulverised fuel was heated to about 600° F. before being admitted to the combustion chamber, and there are certain advantages to be gained by this preheating of the air.

In the process of steam generation there is a great loss of heat, if not the greatest loss, due to the heat being carried away in the escaping flue gases, and it has been shown that this loss is roughly proportional to the difference in the temperature of the gases and the boiler-house air. It may be stated as an approximate rule that every 30° reduction in the final temperature of the gas will give an increase of about 1 per cent. in overall efficiency. Another important factor in this connection is the CO_2 content of the stack gases. It has been stated that an increase of 1 per cent. in the CO_2 content will be responsible for an increase of anything up to 2 per cent. in overall efficiency.

For these reasons it will be seen that the advantages of preheating the air for combustion by the stack gases are twofold ; it not only constitutes an efficient means of reclaiming a large proportion of the heat that would otherwise be wasted, but by providing heated air for combustion it greatly facilitates the burning of the fuel and renders possible a higher CO_2 content in these gases, and this without producing smoke or increasing the carbon in ash losses.

Pulverising Plant

Coal, in a powdered form, may be admitted into the furnace either by what is termed the " unit " method or by the " multiple " method. In the unit method a separate pulveriser is used for each furnace, a very economical and efficient pulveriser being the Raymond-Lopulco Mill. Among the advantages of this pulveriser, which is of recent design, are that the wear and tear are very slight, and even should one of the three rollers become too worn to be efficient a new one can be fitted at a low cost and whilst the mill is at work. Also, the bull ring, into which the rollers fit, is made in three separate sections, which admits of easy replacements when necessary.

In the multiple method, shown diagrammatically in Fig. 121, the coal is crushed into small lumps, foreign matter is extracted, and the coal is then dried before being admitted to the storage bin. From the storage bin it is then fed to the pulverising mill, from which it is sent in powder form by means of a fan into the cyclone collector. The powdered coal drops from the collector on to some form of conveyer from which it is admitted into a number of pulverised coal bins, the number of these bins depending on the number of furnaces to be charged. The quantity of coal to be sent into the furnace is regulated, mixed with the necessary amount of air, and burnt.

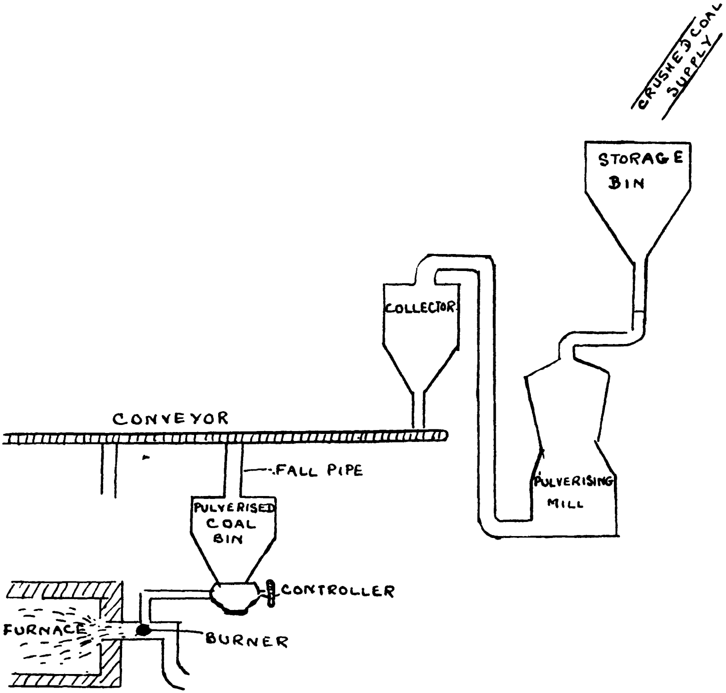


FIG. 121.

The Louvre Stoker

It has already been stated that it will not be possible to work a power plant economically unless efficient methods of combustion are adopted, and in this connection the Underfeed Stoker Co., of London, after years of experience and research, designed what is known as the Louvre or " L " type of stoker. This stoker was first placed on the market in 1926 in order to meet the requirements due to the increasing size of water-tube boilers, and it marks an epoch in the history of travelling grate stoker design.

Although this machine was primarily intended for new and large boilers, it has in some places been fitted to an old boiler with considerable increase in efficiency and output. It possesses a perfect system of air control and distribution and definitely solves problems connected with clinkers and carbon-in-ash losses. In addition, there are other factors of great value with regard to reliability, flexibility, accessibility, and low maintenance costs, all of which have a direct bearing on the economical working of a power plant. Reports on the excellent results obtained under varying conditions of load spread rapidly, and at the present time (1934) we find the " L " stoker at work in eleven countries outside the British Isles.

The Louvre stoker is made up in two styles, one being known as the single machine, the other being the twin machine. The former type is shown in Fig. 122, and is made in widths up to and including 14 ft. 3 in., the twin type being more than double that width.

In the design of a mechanical stoker two problems have to be solved : one relates to the air distribution system and the other deals with the travelling grate, and to a great extent the solution to each of these problems influences the other.

In order to admit the necessary amount of air for varying requirements of the fuel bed, air valves are arranged transversely in a number of rows immediately below the travelling grate, the air controls being shown in Fig. 122. The arrangement ensures uniform admission of air over the whole width of the stoker and renders unnecessary the admission of a supplementary air supply over the furnace.

Another feature of this machine is the automatic cleaning of the grate surface. The most satisfactory air supply and

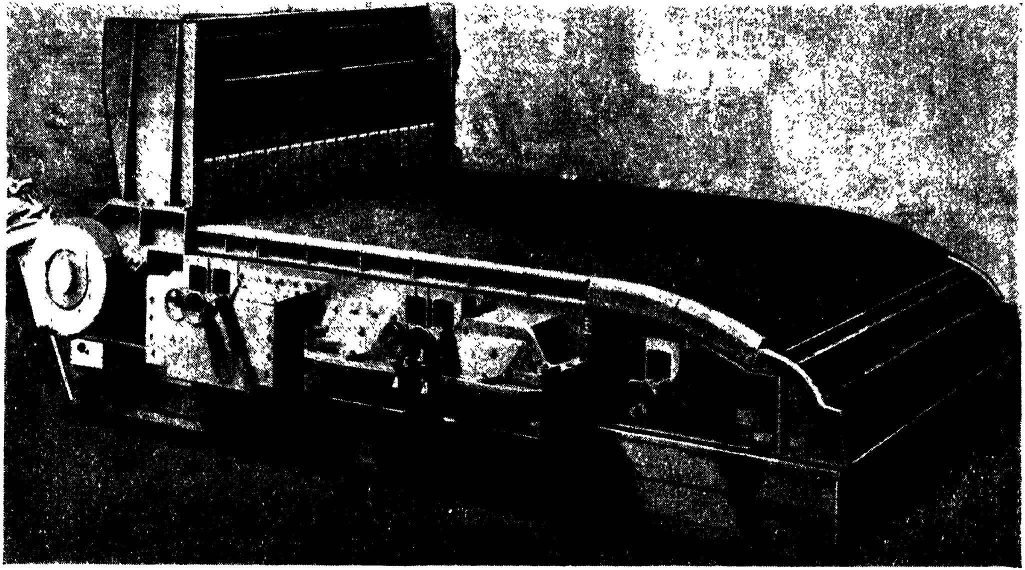


FIG. 122.

regulation will be useless if the spaces are allowed to become affected by the adhesion of clinker, or by distortion due to heat, or by what is known as growth due to oxidation of the metal parts. In order to overcome difficulties caused by the closing of the air spaces the design of the machine has been such as to enable the grate-bars to clean themselves automatically by rubbing against each other when they pass round the front and rear shafts. The fire-bars are pivoted at their ends from holders arranged on tension chains and carry the fire to the sloping end at the rear of the stoker shown in Fig. 122. As soon as the grate travels round the shaft the fire-bars overbalance and rotate on their pivots through an angle of about 90°, this action also being seen in Fig. 122. Each holder carries six fire-bars and each fire-bar has its own pivot, so that the bars do not overbalance one by one but in batches of six, the movement of each set of bars being arrested by the preceding set. The bars are further cleaned as they travel underneath the furnace and are ready to enter again at the front end perfectly clean.

A frequent source of trouble in connection with a travelling grate has been the loss due to small particles of coal falling through the air spaces. It is impossible to prevent some coal-dust falling through, but the " L " stoker reduces this quantity to a minimum. In the course of time even small particles of fuel falling through the bars would interfere with the air supply, so that it is essential to eliminate them. In the Louvre stoker these deposits are discharged from troughs into a hopper, which is arranged under the stoker in front of the ash hopper, as the bars overturn when passing round the rear drum. This means that the whole of the deposits or siftings are discharged at a particular point and are then dealt with by the ash-handling apparatus. It may be mentioned that in this method the value of the combustible matter contained in the siftings is not sufficient to justify their being taken back to the stoker in order to be reburned.

The fuel hopper, which controls the flow of fuel on to the travelling grate, is designed differently from the usual type and possesses one or two special features. Its capacity is large and it is fitted with a cut-off gate which extends the whole width of the grate. The chief function of this gate is, of course, to control the flow of fuel, but in addition it provides access to the furnace during banking and similar operations.

This simplifies the construction of the hopper, as it is not necessary to fit swinging doors or apron plates, which are very often easily damaged. There is an adjustable feed regulating shutter having a thick fire-brick facing, and the shutter is controlled by a worm-gear behind the hopper. A pointer moves over an index plate which shows the thickness of the fuel bed at all times, and in order to prevent leakage of fuel from the hopper the end plates overlap the edges of the travelling grate.

The frame of the Louvre stoker is built up in position before the building of the furnace, and may be regarded as a permanent fixture. By this method of construction there is no possibility of the stoker being a bad fit in the furnace. The side wall brickwork is built on to the side frames of the stoker, which ensures perfectly air-tight joints between the two.

With regard to the performace of this type of stoker it may be mentioned that many varieties of coal, including anthracite duff, which has always been considered unusable, have been successfully consumed, and at a high rate per square foot of grate surface per hour. Reports from users of the machine show that it is able to withstand the effects of high rates of combustion at very high air temperatures over long periods without attention. This, of course, means that the wear and tear is very slight, or, in other words, the cost of furnace maintenance is considerably reduced.

CHAPTER XII

THE STEAM BOILER

In the previous chapter reference was made to fire-tube and water-tube boilers, these being the two main headings under which steam boilers are classified. In the fire-tube or internally fired type the primary heating surfaces are in compression, examples of boilers belonging to this class being the Lancashire, Cornish, Galloway, locomotive, and the common vertical boiler. In the water-tube or externally fired type the primary heating surfaces are subject to tensile stress, examples of boilers belonging to this class being the John Thompson, Babcock & Wilcox, Yarrow, and Stirling.

In this work, space will only permit of a description of one boiler belonging to each class, but before describing these boilers we ought to discuss one or two points and compare the two broad classifications.

The externally fired boiler was the first on the market, and in its original form it was simply a shell with the fire placed underneath. They were regarded essentially as large steam and water containers fired under the bottom, and this part, which received all the deposited impurities from the water, became overheated, with the result that explosions were frequent. The only virtue of such a type of boiler was its cheapness and simplicity, and nowadays the type is very seldom used.

The Cornish boiler has one fire tube or flue, and the Lancashire boiler, which is larger than the Cornish type, has two, and it is interesting to note that originally these types were not built as internally fired boilers, because the fire was placed underneath the shell and the flues were fitted merely to allow extra heating surface. (A modern Lancashire boiler is shown in Fig. 123, and will be described presently.)

Before making a decision as to what type of boiler should be installed full details must be given as to what work the boiler will have to perform. Also, available conditions such as floor space, condition of feed water, draught, etc., must receive careful attention. If it is decided to install a water-tube boiler the most essential condition is that the feed water must be pure and that it does not become unduly dense owing to the concentration of insoluble matter.

Each type of boiler possesses certain advantages, and the following points refer to the fire-tube type, one of the most important boilers of this type being the Lancashire boiler.

Such boilers are robust in construction ; the shell and the tubes are comparatively large and have to be made correspondingly thick in order to withstand the pressure. An advantage of this is that corrosion of a given depth will have a less weakening effect than it will have on the thinner plates of the smaller drums and on the water tubes of the externally fired type. In practice it has been found that the fire-tube boiler is very economical in upkeep costs, and one reason for this is because practically no brickwork is subject to primary heat. There is a large reservoir of steam available owing to the large water and steam spaces, and when sudden or varying demands are made for steam this is of great value.

With regard to the question of economy, the comparatively small heating surface of the fire-tube boiler can be conveniently increased by means of a water heater or, as it is called, an economiser, which is placed in the path of the flue gases before they leave at the chimney. The temperature of the flue gases as they reach the economiser will be considerably reduced so that soot will be deposited on the heating surfaces of the economiser, and this deposit of soot will prevent the heat reaching the water. In order to overcome this difficulty it is usual to employ automatic scrapers on the tubes of the economiser in order to keep the surfaces clean and efficient. Recent developments in the design and construction of the Lancashire boiler have made it, together with its accessories, the economiser, air heater, and superheater, a very practical unit, combining a high efficiency with a large storage capacity and a low upkeep cost.

The water-tube boiler has many compensating advantages and is universally used in high-class power stations. It is more efficient as a steam generator than the other type, and is free from the strict limitation in the size of the fire as applied to the Lancashire type, and because of this the steam available from a water-tube boiler per square foot of ground space is

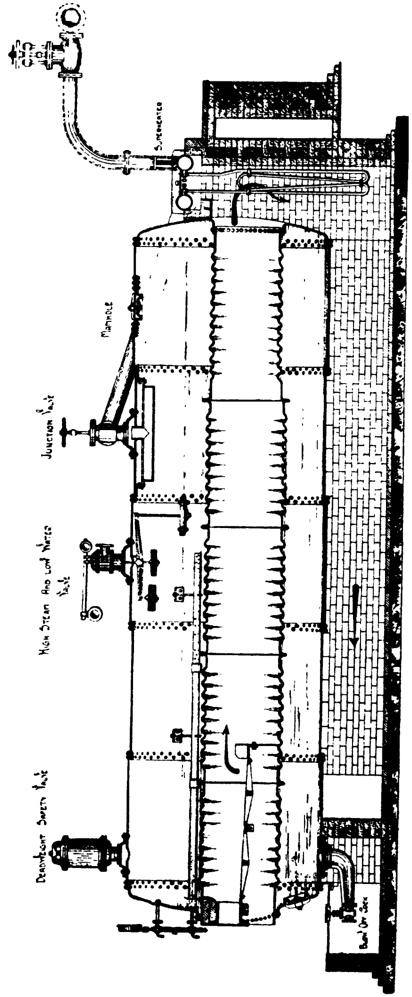

Superheater
Manhole
Junction Valve
High Steam and Low Water Valve
Deadweight Safety Valve
Blow Off Cock

FIG. 123.

very much greater. Also, there are possibilities of development in the boiler setting, such as the provision of superheaters, water heaters, air heaters, etc., which have made possible the remarkable recent development of efficiency, high steam temperature, and output of boilers used in power stations. Further, in the question of economy there is much more than mere pounds of steam per pound of fuel, and usually the final criterion from the owner's point of view is the total output against the total cost.

In many cases, and especially where conditions admit of only intermittent working and short hours, it would be better to employ a simple and therefore cheap plant, but for continuous working it would be advisable to instal the more elaborate plant, the first cost and charges in the latter case being smaller in relation to the fuel savings. On the other hand, the total saving of fuel which would be possible in a boiler working short hours would not warrant the cost of a high efficiency plant.

The object of a steam boiler is to convert water into steam at the desired rate of evaporation and at the desired temperature and pressure safely, efficiently, and at a suitable capital cost and overall efficiency, after taking into account capital charges, depreciation, wages, etc., and for power production on a large scale the water-tube boiler is undoubtedly the best proposition. The diameter of its elements, such as the tubes, drums, etc., is small, so that it can easily be constructed of suitable strength. Its heating surface can be extended and its fire-grate area, on which primarily a boiler's steaming capacity must be based, is much larger in relation to the total ground space than in the fire-tube type as already mentioned.

The water-tube boiler consists essentially of one or more groups of water tubes suitably disposed about the furnace and so arranged as to collect as much as possible of the radiant heat from the furnace, and to provide that as far as possible their surfaces shall be swept by the hot gases. Fig. 124 illustrates a John Thompson water-tube boiler and shows the general arrangement of the elements.

In order to provide for a free water circulation a steam space of sufficient volume must be provided in order to prevent water being delivered instead of steam, and it is necessary to have a steam-freeing surface large enough to allow the steam to separate from the water without undue disturbance. The tubes are connected with one or more steam and water drums at the top and water drums or headers at the bottom, but these are arranged differently in different makes of boilers. They should be inclined from the horizontal in order that the water may flow in one direction under the influence of heat, the usual inclination being from about 15° to almost vertical. Apparently the vertical position would be the most advantageous in allowing a free upward movement, but it has been found that bubbles formed on the surface of a vertical tube do not free themselves easily, but tend to cling or crawl up the surface rather than to float off. For that reason vertical tubes are not favoured as primary heating surfaces.

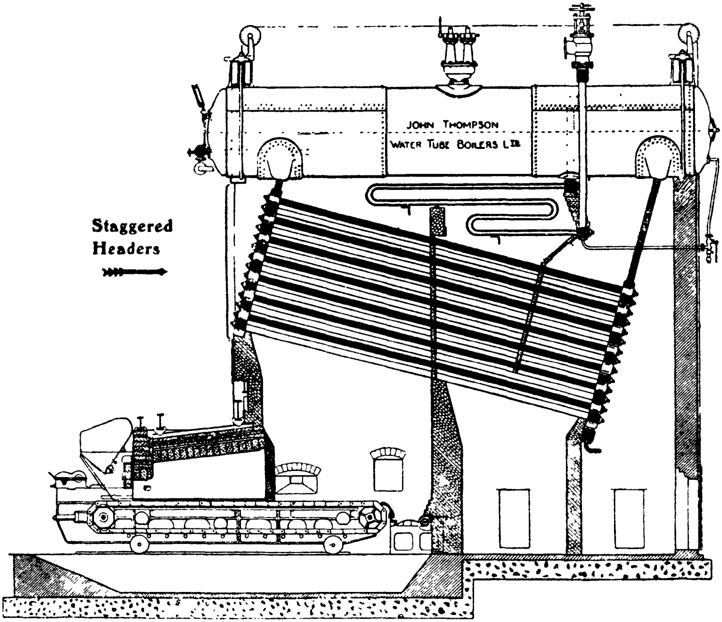


FIG. 124.

Care and Management of Steam Boilers

This is a very important section of the work with which the engineer has to deal, and in order to discuss it thoroughly it would require a volume devoted to that subject only. In this work, however, we can consider one or two essentials which are necessary for the efficient and economical working of boilers.

Causes of waste due to wrong methods of stoking and due to incomplete combustion of fuel were mentioned in the previous chapter and need not be repeated here. It has been proved in practice that the best results will be obtained from a boiler when a light smoke is being discharged. Entire absence of smoke, except, of course, in the case of smokeless fuel, and excessive smoke both spell waste. The former would mean that considerable heat was passing away at the chimney in the form of useless hot air which may have been admitted in excess above the furnace or through cracks in the brickwork setting. The latter, as was mentioned in the previous chapter, would be caused by wrong methods of stoking, or it may be due to restricted air over the furnace, or due to the doors being insufficiently opened. Steam should not be raised, neither should the boiler be allowed to cool rapidly, as owing to unequal expansion and contraction, trouble will be caused through leaky joints, which may cause a boiler to empty itself overnight or even whilst steam is being raised.

All boiler fittings should be tested regularly, and it will be necessary to test the glass water gauges (these are shown on the front of the boilers in Figs. 123 and 124) before starting up the fires and even whilst steam is being raised. If these gauges are not in proper working order, the boiler may empty itself without any warning, and in the case of fire-tube boilers this will mean bulged furnaces or leaky tubes. In the case of water-tube boilers insufficient water will cause leaks in the water tubes and even in the main drums. In the event of shortness of water it is imperative that the furnace plates on the water side should be cooled by turning on all the available feed water, and the fires should be damped down by covering them with ashes. In water-tube boilers large quantities of heat will be stored in the brick settings, and one should not overlook the possible danger of this heat evaporating the water when the boiler is standing idle.

Internal corrosion of boilers is due to dissolved air in the feed water and in the course of time may have serious results. In order to prevent corrosion, vegetable extracts such as tannin or caustic soda should be added to the feed water at frequent and regular intervals. The caustic soda neutralises the acidity in the water, and the tannin absorbs the oxygen of the dissolved air. It is often necessary to blow down the boiler in order to get rid of dense water which contains neutral salts, because these salts accelerate the internal corrosion which results from the above-mentioned causes.

Scale and sediments are introduced into a boiler with the feed water, in which they are dissolved and from which they separate as the water is evaporated, and are a frequent source of trouble. Hard scales contain sulphate of lime (plaster of paris), but the addition of soda ash to the feed water will convert this into the softer carbonate of lime (chalk). It should be mentioned that no treatment of the water in the boiler will reduce the amount of this deposit, but it certainly alters its character and facilitates cleaning operations. Perhaps the most effective way of reducing the deposit is to use special water-softening plants before the water is admitted into the boiler. Water-softening plants consist of vessels into which the feed water is admitted mixed with certain chemicals in the correct proportion which cause the scale-forming impurities to be precipitated, the precipitates being removed first by settling tanks and then by filters.

External corrosion is usually found under damp coverings, walls, etc., and all leakages from tubes or shells should be stopped. Also, steps should be taken to prevent drippings from roofs, steam-pipe flanges, etc., from falling on to boiler coverings, and a suspected leak should be reported as soon as possible.

Boilers out of action for a short period should be kept in a warm condition, more especially if they contain water ready for use, otherwise dampness will cause serious corrosion. A boiler which is laid off for any length of time should be scaled, washed, and dried, and it is a good policy to place trays of unslaked lime inside and close all openings in order to exclude damp air. It has been found that boilers which have not been closed up in this manner deteriorate much more rapidly than those which are in use.

Boiler Inspection

All boilers should be inspected at least once a year, and before inspection the boiler must be completely opened out, flues swept, and all scale removed. The inspector pays special attention to the condition of the plates, all points of contact with brick settings, leakage of seams, signs of overheating, furnaces, and all joints and stays. All parts of the boiler must be accessible, and this should be a factor in choosing a boiler, especially if it has to be used in a place where clean water is not available.

Boiler Fittings

The fittings which are usually found on a boiler are shown in position in Fig. 123. First of all we have the blow-off valve, which should be fitted to the lowest part of a boiler. The object of this is to clear out any sediment which may form in the water space, or it may be used to empty the boiler when it is necessary to make an internal examination. The pressure-gauge and water-gauge glasses are seen on the front of the boiler in Fig. 123. The former indicates the steam pressure in the boiler, and the latter, usually two glasses, show the level of the water. The top cock is open to steam and the lower one is open to the water space, the glass being held in position between these cocks by means of stuffing-boxes. Ball valves are usually fitted between each cock and the glass, so that should the latter be broken both the supply of steam and water will automatically be cut off.

On the top of the boiler, from left to right in Fig. 123, we have the deadweight safety valve, high-steam and low-water valve, the junction valve, and the manhole. The deadweight safety valve is loaded so that if the steam pressure exceeds a certain amount the steam will blow off. In this valve a spring may be used to hold the valve on its seating instead of the deadweight, or, as in the case of the high-steam and low-water valve, a lever may be used. There is a disadvantage in using a lever safety valve due to the fact that it may not act until the steam pressure is above that for which the valve has been set. No matter what type of safety valve is fitted to a boiler it is essential to examine it frequently in order to make sure that it is in proper working order and that the valve and its seating are not suffering from the effects of corrosion.

The high-steam and low-water valve shows, as its name implies, when the steam pressure is too high or when the water-level is too low. The lever safety valve will act as a check on the deadweight safety valve. It will, of course, act instead of the deadweight valve should this for any reason be out of order. The weights and float shown in Fig. 123 are in equilibrium when the water-level is normal, but should the level fall the float will cause the lever to turn clockwise about a point to the right of the vertical spindle shown in the diagram. During this operation the spindle rises and lifts the valve from its seating so that steam escapes, showing that something is wrong. The attendant then notices his pressure gauge and water-level and makes the necessary adjustments.

The junction valve or stop valve is the next fitting shown in Fig. 123. The object of this is to allow steam to pass from the boiler to the engine, and it consists of a valve which can be opened or closed by a screwed spindle rotated by a hand-wheel as shown. If the spindle is raised, the pressure of the steam in the boiler will be sufficient to lift the valve so that the steam can flow along the steam pipe, through a super-heater, and then to the engine where it performs its work. Great care must be exercised when steam valves are opened, because whenever steam and water meet in a closed space what is known as water hammer may occur, and in the case of high-steam pressures and large volumes of cold water, which may have collected in long pipes, the force due to water hammer may be sufficient to fracture even the strongest steel pipes. As soon as steam has been turned off drains should be opened, but on no account should the drain in a steam pipe be open before the steam valve has been closed.

When water passes with the steam into the steam pipes the boiler is said to prime, and this may happen when the steam pressure is too high or if the steam space is too small. The anti-priming pipe shown underneath the junction valve in Fig. 123 is intended to prevent priming. Steam passing through this pipe has its direction of flow changed suddenly, with the result that water is thrown out of suspension and drains back through holes in the pipe into the boiler.

The manhole cover may be removed in order to allow a man to enter the boiler for inspection or for cleaning the interior.

Before concluding this chapter we ought briefly to consider the working of a complete power plant, a diagrammatic representation of which is given in Fig. 125.

In this diagram a water-tube boiler is illustrated and it shows the path of the hot gases as they pass from the furnace round the water tubes N2 and the superheater N5 on their way to the chimney.

As soon as the steam formed from the water in the boiler N reaches the necessary temperature and pressure the boiler stop valve 6 is opened and the steam of suitable quality passes along the steam pipe 7 on its way to the engine cylinder A. Before entering the cylinder by means of the engine stop valve 9 the steam passes through a steam separator 8, the object of which is to remove water and impurities which may pass along with the steam. When these impurities enter an engine cylinder they mix with the lubricating oil and form a thick paste, which adheres to the valves, ports, and passages, and enters the spaces between and behind the piston rings. The piston rings then fail to prevent the steam from passing to the opposite end of the cylinder and this results in excessive wear on the moving parts and in loss of power.

After performing its work in the engine cylinder, as described in the next chapter, the steam is exhausted either into the atmosphere or into a condenser. When exhausting into the atmosphere the steam from the engine, as shown in Fig. 125, would pass through a non-return valve 21 and then along the pipe 22 to the atmosphere.

Instead of exhausting into the atmosphere an engine may exhaust into a condenser, and in such a case certain advantages will be gained. For example, as the steam condenses a partial vacuum will be formed and this will have the effect of reducing the back pressure against which the engine piston has to work and so will increase the engine efficiency. Further, the condensed steam, known as the condensate, is taken by means of an air pump from the condenser 13 (Fig. 125) and is sent along the pipe 14 into the hot well 15. The water in the hot well will be at a comparatively high temperature and it is taken by means of a feed pump 2 and sent along the feed pipe 3 back to the boiler at a higher temperature than it would be if it were taken direct from the mains.

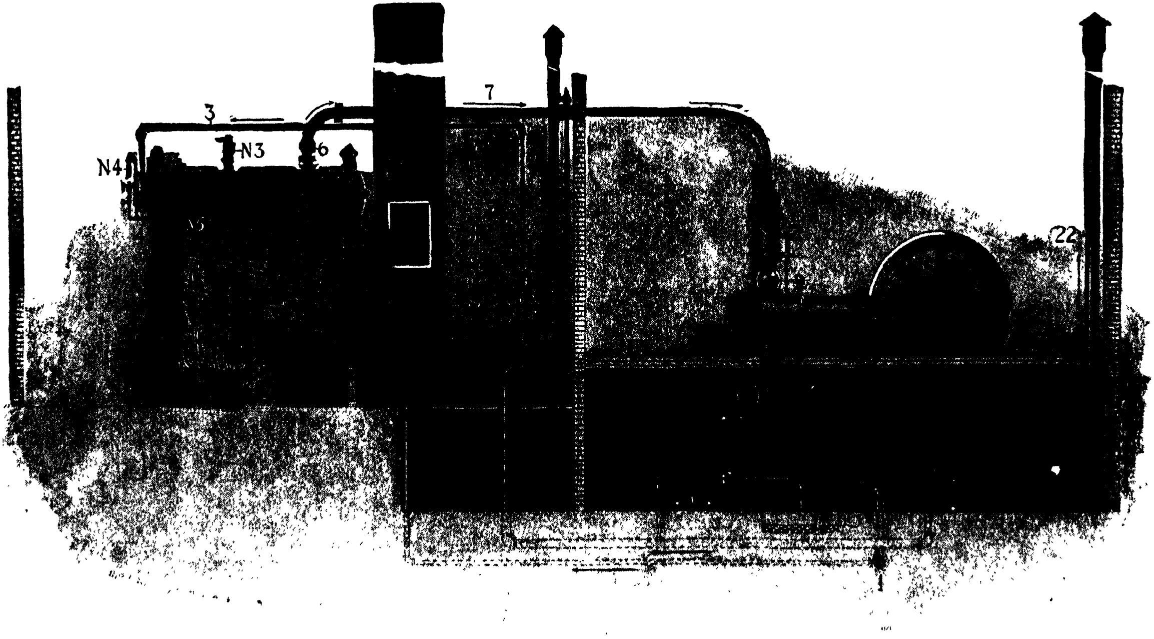


FIG. 125.

While discussing condensers it may be mentioned that they are divided into two main types known as the jet condenser and the surface condenser, each type of which has its advantages and disadvantages. In the first place, if suitable cooling water is available the jet condenser would be cheaper than the surface condenser and would require less cooling water in a given time. On the other hand, owing to the amount of air in solution with the injection water in a jet condenser, a larger air pump would be required than would be the case with a surface condenser and a greater power would be required in order to drive the pump. The surface condenser is specially suitable for marine work, as sea water can be used for cooling purposes without the risk of boiler corrosion, which would soon result if the feed water were mixed with brine.

In connection with the surface condenser there has always been serious trouble due to the corrosion of the tubes, and this trouble is due to a variety of causes. A considerable amount of research work has been undertaken in order to eliminate the trouble, and according to reports fairly satisfactory results have been obtained by replacing the ordinary brass tubes by special alloy tubes composed of copper and nickel. It has been stated that the life of a cupro-nickel tube is more than five times that of the ordinary brass tube and that the cost is little over twice as much. Another point in favour of these special alloy tubes is that there will be no danger of corrosive substances passing along with the feed water into the boiler.

Example 1.—The following particulars refer to a trial of a water-tube boiler :—

Coal fired per hour, 2,200 lbs. ; calorific value of coal used=14,000 B.Th.U. per lb.

Water evaporated per hour, 21,000 lbs.

Temperature of feed water entering the boiler, 140° F.

Temperature of water entering the economiser, 80° F.

Steam pressure, 200 lbs. per sq. in. (absolute).

Saturation temperature, 384° F. Superheat temperature, 535° F.

Determine (*a*) the efficiency of the boiler alone, assuming the steam to be dry and saturated, (*b*) the overall efficiency. (Specific heat of superheated steam may be taken as 0·56.)

The efficiency of a boiler is the ratio

$$\frac{\text{Heat given to the water}}{\text{Heat supplied by the coal}},$$

and when the efficiencies of the economiser and superheater are taken into account the result is known as the overall efficiency of the plant.

From Callendar's steam tables we find that at a pressure of 200 lbs. per sq. in. (absolute) the latent heat of steam is 849·96 B.Th.U. per lb. Heat of formation per pound will therefore be $(384-140)+849{\cdot}96=1093{\cdot}96$ B.Th.U.

(*a*) Efficiency of boiler alone is therefore

$$\frac{21000\times 1093{\cdot}96}{2200\times 14000}=74{\cdot}6 \text{ per cent.}$$

(*b*) Taking the economiser and superheater into account the heat of formation per pound will be

$$(384-80)+849{\cdot}96+0{\cdot}56(535-384)=304+849{\cdot}96+84{\cdot}56$$
$$=1238{\cdot}5 \text{ B.Th.U.}$$

Overall efficiency is therefore

$$\frac{21000\times 1238{\cdot}5}{2200\times 14000}=84{\cdot}4 \text{ per cent.}$$

TENTH SET OF EXAMPLES

1. Write a short essay on " Economical Combustion."

2. The following percentage analysis by weight was obtained from a sample of anthracite coal : Carbon, 91 ; hydrogen, 5 ; oxygen, 2·5, the remainder being ash. Given that the calorific value per pound of hydrogen=34,500 C.H.U. and of carbon=8,080 C.H.U., determine the calorific value of anthracite. Also determine the theoretical amount of air required for its complete combustion.

3. A sample of petrol was tested with the following results : Percentage analysis by weight : Carbon, 85 ; hydrogen, 12, and oxygen, 3. Determine the calorific value of petrol, taking the calorific value of hydrogen as 62,000 B.Th.U. per lb. and that of carbon as 14,000 B.Th.U. per lb.

4. Explain briefly what you consider to be the more efficient methods of stoking.

5. Explain how you would prepare a boiler for inspection.

6. What is the object of an "economiser"? Explain its action and sketch its position in relation to the boiler.
U.L.C.I.

7. Compare the methods of furnace firing by (*a*) mechanical stokers, (*b*) hand-firing. Explain and illustrate a type of mechanical stoker. U.L.C.I.

8. Sketch and describe a steam gauge, and explain the principle on which it works. U.L.C.I.

9. A Lancashire boiler generates per hour 5,200 lbs. of dry steam at an absolute pressure of 160 lbs. per sq. in. The grate area is 34 sq. ft. and 18 lbs. of coal are burnt per square foot of grate area per hour. The calorific value of the coal is 7,900 C.H.U. per lb. and the temperature of the feed water is 17·5° C. Find the efficiency of the boiler given :

Steam Pressure.	Temperature.	Sensible Heat per Pound.	Total Heat per Pound.
Lbs. per Sq. In. 160	° C. 184·2	Cent. Heat Units. 186·6	Cent. Heat Units. 667·2

U.L.C.I.

10. Explain the meaning of the term "equivalent evaporation." A boiler evaporates 10 lbs. of water per pound of coal. The steam pressure is 100 lbs. per sq. in. absolute and the feed water temperature is 80° C. Determine the equivalent evaporation from and at 100° C. (At a pressure of 100 lbs. per sq. in. absolute, temperature=164·28° C. and latent heat =496·1 C.H.U. per lb.)

11. Describe what type of boiler you would instal in a small power station. Explain the function of the various fittings and by means of a sketch indicate their respective positions on the boiler.

12. A firm of engineers offers a simple steam engine at a certain price, but state that if the engine is intended to run condensing the necessary fittings will be charged extra. Describe fully these extra fittings and state their functions. What advantage, if any, would there be in running the engine condensing? U.L.C.I.

CHAPTER XIII

THE STEAM ENGINE

WE are told by authors of books on the history of engineering progress that it is possible to trace back to very early times the idea that steam could be used to generate power, but no results of very great importance, at any rate from a practical point of view, seem to have been achieved until the end of the seventeenth and beginning of the eighteenth centuries. By this time a practical steam engine was on the market, and experiments performed by Papin and Newcomen were made the foundations for subsequent improvements and developments carried out by James Watt (1736-1819).

Watt very carefully studied many problems connected with the performance of a steam engine and arrived at definite conclusions with regard to loss of heat in the cylinder walls. As a result of his investigations he designed a cover for the top of the cylinder and allowed steam from the boiler to enter so as to reduce the cooling effects of the air. He is also responsible for the use of a separate condenser in connection with an engine, and was the first to realise that a higher efficiency could be obtained if steam were cut off early in the stroke and its expansive properties were utilised. Other improvements due to Watt relate to the governor, indicator and the crank and connecting-rod mechanism. The last-named is used to convert reciprocating motion into rotary motion. By 1784 he had made the engine double acting, *i.e.*, the steam acts on both sides of the piston instead of acting only on one side as had been the case up to that date.

From the time of Watt onwards other improvements were gradually brought about, and factors which contributed to the better working generally of the steam engine include better boiler design, which meant higher steam pressures, the use of superheated steam, multi-cylinder engines, the uniflow engine, and the steam turbine.

The diagram in Fig. 126 represents the elevation and plan of a single-cylinder double-acting steam engine, and we must now discuss the working of such a machine.

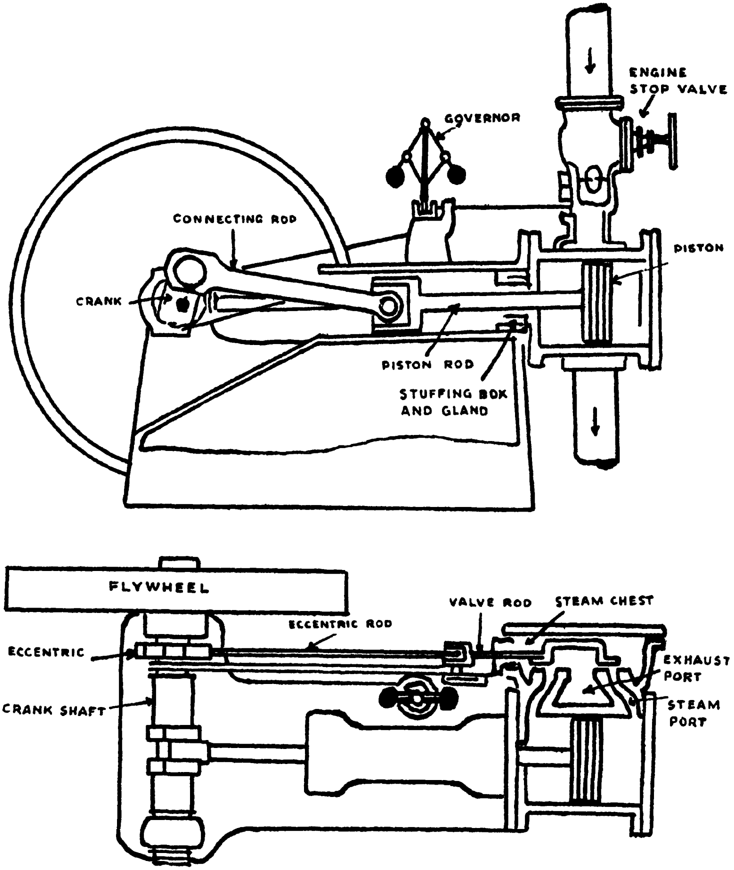


FIG. 126.

Steam is admitted into the steam chest by means of the engine stop valve shown, and its admission into the engine cylinder is controlled by means of a slide valve.

In the position shown in plan (Fig. 126), steam enters the cylinder through the steam port on the right, and it causes the piston to move to the left. When the piston has travelled a certain fraction of its stroke the slide valve would be moving to the right and will cut off the steam so that the steam in the cylinder would work by expansion. This would continue until the inner edge of the valve uncovers the port on the right, and the steam in the cylinder on the right of the piston is then said to be released. Just before the end of the outstroke of the piston the valve moving to the right would uncover the left steam port, steam would enter and force the piston back to the right, and during this stroke steam remaining in the cylinder would be sent out through the exhaust. The motion of the slide valve is controlled by the eccentric in such a way that it would again be moving towards the left before the piston reaches the end of its travel towards the right, and at a certain instant the port on the right would be covered by the valve, the result being that the piston compresses the steam remaining in the cylinder, the steam so compressed being called cushion steam. The cycle of events, admission, cut off, release, and compression, would then be repeated, and we shall discuss them a little more fully presently.

The reciprocating motion of the piston is converted into rotary motion at the crankshaft by means of the crank and connecting-rod mechanism, and in order to keep this rotary motion fairly uniform a flywheel is fitted to the crankshaft, as shown in Fig. 126. The steam acting on the piston will have its energy transmitted to the flywheel, and the amount transmitted will vary from zero when the crank and connecting-rod are in one straight line, *i.e.*, when the piston is at its dead centres, to a maximum when the energy is transmitted by the connecting-rod in a direction at right angles to the crank. As the turning effort on the crank increases from its minimum to its maximum value the speed of the engine would increase, and the speed of the engine would fall as the turning effort decreased from its maximum to its minimum value. This variation in speed is resisted by the flywheel, which, owing to its mass, stores up energy as the turning effort increases, and this energy is given out as the turning effort decreases, with the result that the piston is carried past its dead centres and the variation in speed of the crankshaft is confined to very narrow limits.

Another method of controlling the speed of an engine is by means of a governor, that shown in Fig. 126 being known as a Watt governor. The governor is driven by means of a belt from a convenient point on the crankshaft, and as the speed of the latter increases there will be a corresponding increase in the rotational speed of the governor. This in turn, by means of a system of links, will close the throttle shown below the engine stop valve in Fig. 126, with the result that less steam will be admitted to the engine cylinder, and consequently the speed will be reduced. As the speed of the engine falls that of the governor will fall also, and the throttle will again be opened to admit more steam to the cylinder, so that with a sensitive governor it is possible to keep the engine speed within certain narrow limits. It should be mentioned that if a governor is too sensitive the throttle valve will open too much for a certain change in speed, and this, of course, will mean that too much steam is being admitted to the cylinder and the engine speed will be too great. The valve will then be closed too rapidly and will cause a rapid fall in the speed of the engine. The variation in speed due to the above-mentioned cause is known as "hunting."

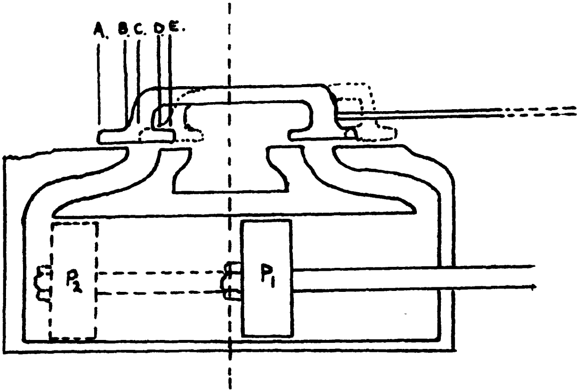


FIG. 127.

We must now return to the steam-engine cylinder, but before discussing the action of the steam on the piston we have to consider the motion of the slide valve and piston, and also the motion of the crank relative to the eccentric.

Fig. 127 represents a steam-engine cylinder piston and slide valve. When the piston is at the point, say P_1, the slide valve will be in the position as shown by the full-line drawing, *i.e.*, it is at the centre of its travel. When the valve is in this position the amount by which it overlaps the ports is called the lap of the valve, the amount AB being known as the steam or outside lap, and the amount represented by DE being known as the exhaust or inside lap. Before steam can be admitted into the cylinder the valve must move either to the right or to the left in order to uncover one or other of the steam ports. Suppose the piston moves from P_1 to P_2, then the valve will have to be moved to the right into the position, as shown by the dotted-line drawing. The steam port on the left will then be uncovered by an amount represented by BC, and this amount of opening is called the lead of the valve. The maximum opening of the port to admit steam will depend on the setting of the valve and may be anything up to the total width of the port. For any setting of the valve its travel will be given by 2 (steam lap+maximum opening to steam), and the eccentricity of a valve is simply half its travel.

Motion of the Crank and Eccentric

In Fig. 128 two concentric circles are shown, the outer one representing the crank circle and the inner one the eccentric circle. When the valve is at the centre of its travel, as shown in the full-line drawing in Fig. 127, the line OE in Fig. 128 can be drawn to represent the corresponding position of the eccentric. We have seen that to admit steam into the cylinder the valve must move to the right, and when the piston is just commencing its outward stroke the valve must be moved by an amount equal to the steam lap+the lead. From the point O (Fig. 128) mark off a length OA=steam lap and AB=the given lead. From B draw the vertical line BE′, then E′ will represent the position of the eccentric when the piston is beginning its forward stroke, *i.e.*, when the crank OC in Fig. 128 is horizontal. The angle EOE′ by which the eccentric leads the crank in excess of 90° is called the angle of advance of the eccentric, the total angle COE′ being called the angular advance.

We are now in a position to consider a simple graphical construction, by means of which we can show the relative positions of the crank and eccentric, and we shall do this by taking a numerical example.

Example 1.—The travel of a slide valve is $2\frac{1}{2}$ in., the steam lap is $\frac{1}{2}$ in., and the lead $\frac{1}{8}$ in. Determine the angle of advance at which the eccentric must be set and show the crank positions when steam is admitted to the cylinder, cut off, released, and compressed.

By the method just explained the angle of advance is found to be 30° (Fig. 129). The angular advance, *i.e.*, $\widehat{COE}$, is therefore 120°, so that the eccentric will always be ahead of the crank by this amount. When the eccentric is at E the crank OC will be horizontal, *i.e.*, the piston will be at the end of its stroke. If we move the eccentric to the position E_1, the valve will move through a distance equal to the given lead, viz., $\frac{1}{8}$ in., and will then be just on the point of opening the port to admit steam into the cylinder. We can therefore see that the crank will be in the position represented by OC_1, *i.e.*, $\widehat{E_1OC_1}=\widehat{EOC}$. By measurement the angle COC_1 in Fig. 129 is found to be $-6°$. This angle is given as a minus

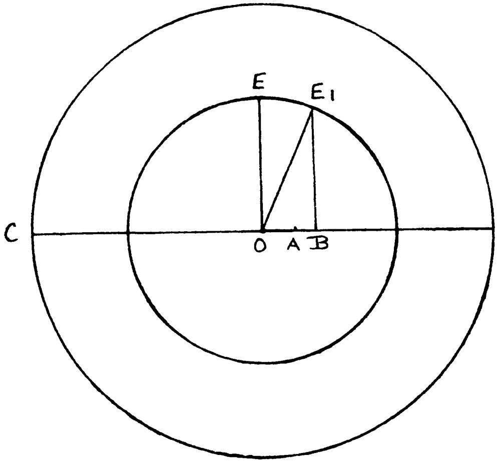


FIG. 128.

quantity because the piston will have a short distance to travel towards the left before beginning its forward stroke.

Since the valve, moving to the right, is just on the point of admitting steam to the cylinder when the eccentric is at E_1, it will be moving to the left and will cut off steam when the eccentric is at E_2, *i.e.*, on the vertical line through E_1, and this will give C_2 as the crank position at cut off, *i.e.*, $\widehat{E_2OC_2}=\widehat{EOC}$. Measuring the angle COC_2 we find it to be 127°.

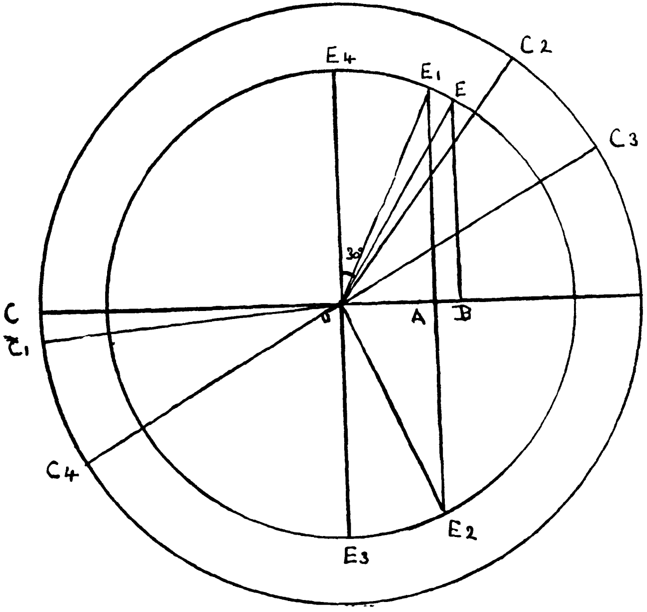


FIG. 129.

In this example there is no exhaust lap, so that when the valve moving to the left is at the centre of its travel, *i.e.*, when the eccentric is at E_3, steam will be on the point of being released, and the corresponding crank position will be at C_3, the $\widehat{E_3OC_3}$ again being made to equal $\widehat{EOC}$. By measurement we find the angle $COC_3=150°$.

Finally, when the valve, moving to the right, is at the centre of its travel the steam remaining in the cylinder will be compressed, and in this case the eccentric position will be E_4 and the crank position will be C_4, and by measurement the angle COC_4 is found to be 330°.

Exercise.—In Fig. 129 the line OC represents the length of the crank. Assume the connecting-rod to be four times this length and construct a diagram showing the piston position at the four points, admission, cut off, release, and compression.

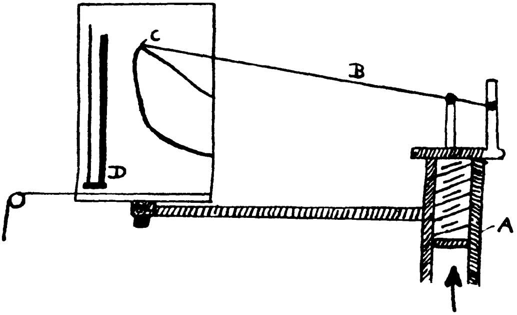


FIG. 130.

The student who continues to study the subject Heat Engines will come across different types of problems relating to the motions of the slide valve and eccentric, and certain valve diagrams, such as the Reuleaux, Zeuner, and Bilgram diagrams, will be used in order to obtain a solution. At the present stage of our work, however, these diagrams need not be discussed, and we must now consider the action of the steam in an engine cylinder.

The action of the steam may be studied, and the indicated horse-power developed may be obtained from an indicator diagram. The indicator, a sketch of which is given in Fig. 130, is fixed on to the engine cylinder and the steam acts in the direction of the arrow as shown. The pressure of the steam compresses the spring A so that the arm B is lifted. On the end of the arm B there is a pencil C which traces out a diagram on a strip of paper placed on the drum D, which is attached to the reciprocating part of the engine. An actual indicator diagram is shown in Fig. 131 in which the scale of the indicator spring is $\frac{1}{80}$. This means that 1 in. height on the diagram represents a pressure of 80 lbs. per sq. in. In order to determine the mean effective pressure of the steam during a stroke the average height of the diagram is found by means of the mid-ordinate rule and the average height is multiplied by the scale of the spring, in this particular case 80.

Exercise.—Determine the mean effective pressure of the steam from the indicator diagram given in Fig. 131.

Study the following worked example in which a method of constructing the ideal or hypothetical indicator diagram and the method of determining the indicated horse-power will be explained.

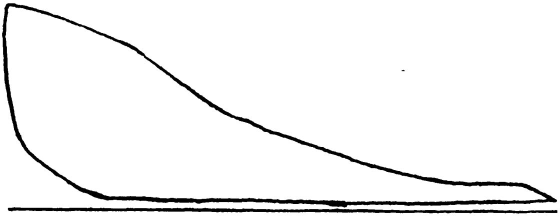


FIG. 131.

Example 2.—Steam enters the cylinder of a double-acting steam engine at a pressure of 150 lbs. per sq. in. absolute and is cut off at $\frac{1}{4}$ stroke. The cylinder diameter is 8 in. and the stroke is 12 in. The back pressure is 16 lbs. per sq. in. and the engine makes 200 revs. per min. Construct a diagram of the work done during a stroke and determine the indicated horse-power. Assume a diagram factor of 0·8.

Draw OA to represent the piston stroke, and draw OB at right angles to OA to represent a pressure of 150 lbs. per sq. in. (Fig. 132).

Complete the rectangle OAFB, and at $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ stroke draw perpendiculars to OA, meeting BF at the points C, D, and E as shown.

Assuming steam to enter the cylinder when the piston is at the beginning of its stroke and its pressure 150 lbs. per sq. in., to remain constant until cut off takes place at $\frac{1}{4}$ stroke, the area OBCG will represent the work done during admission. From $\frac{1}{4}$ stroke until the end of the stroke we assume the steam to expand according to Boyle's Law, and points on the expansion curve may be obtained as follows: Draw the lines DO, EO, and FO, and from the points where these lines cut CG draw horizontals cutting DH at L, EK at M, and FA at N respectively, so that the expansion curve will be CLMN. The work done during expansion will be represented by the area bounded by this expansion curve, the horizontal, and the ordinates at G and A. The diagram so constructed is called the hypothetical indicator diagram, but in practice the diagram would be modified somewhat similar to that shown dotted, the ratio $\frac{\text{area of actual diagram}}{\text{area of hypothetical diagram}}$ being known as the diagram factor, and in this example the ratio is 0·8.

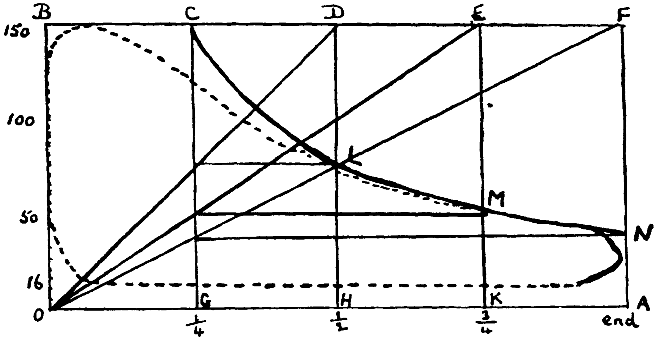


FIG. 132.

Applying the mid-ordinate rule to determine the mean effective pressure of the steam, as given by the diagram in Fig. 132, we find this to be 91·7 lbs. per sq. in., but as there is a back pressure due to atmospheric pressure and steam remaining in the cylinder of 16 lbs. per sq. in., the mean effective pressure must be reduced by an amount equal to the back pressure, giving the result as 75·7 lbs. per sq. in.

Again, in this example the diagram factor is 0·8, so that the required mean effective pressure is $75{\cdot}7 \times 0{\cdot}8 = 60{\cdot}56$ lbs. per sq. in.

If the mean effective pressure of the steam is, say, P lbs. per sq. in. and it acts on a piston of diameter D in., then the force in pounds acting on the piston will be $P \times 0{\cdot}7854D^2$. This force acts for the length of the stroke, say, L ft., so that the work done per stroke will be $P \times 0{\cdot}7854D^2 . L$ ft.-lbs. Now the engine runs at, say, N revs. per min., and it is double-acting (*i.e.*, the steam acts on both sides of the piston), and since 1 H.P. is work done at the rate of 33,000 ft.-lbs. per min., the indicated horse-power will be given by the formula

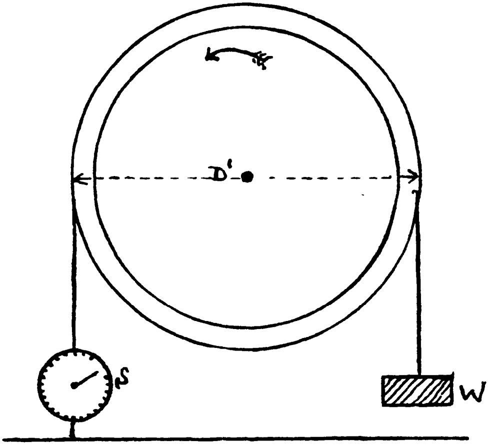


FIG. 133.

$$H = \frac{2 . P . 0{\cdot}7854D^2L . N}{33000}.$$

Using the values given in the above example the required horse-power $H = \frac{2 \times 60{\cdot}56 \times 0{\cdot}7854 \times 64 \times 1 \times 200}{33000} = 36{\cdot}07$.

The power developed by an engine which can be used to drive machinery, etc., is known as the brake horse-power (B.H.P.), and this may be determined by means of a rope brake which passes round the flywheel, as shown in Fig. 133.

One end of the rope carries a deadweight W lbs., and to the other end a spring balance S is attached, and this is fixed to a convenient point on the ground. Let the diameter of the flywheel be D ft. and assume it to rotate in the direction of the arrow at N revs. per min. We assume the effective driving force to be the difference between the deadweight and the spring-balance reading in pounds, *i.e.*, it is (W—S) lbs. The circumference of the wheel in feet will be πD, so that the work done per revolution in foot-pounds will be (W—S)πD. But the engine rotates at N revs. per min., therefore the work done per minute will be (W—S)πDN, and therefore the brake horse-power will be given by the relation $\text{B.H.P.} = \frac{(W-S)\pi DN}{33000}$.

The mechanical efficiency of a steam engine is the ratio $\frac{\text{work given out}}{\text{work put in}}$, *i.e.*, it is the ratio $\frac{\text{brake horse-power}}{\text{indicated horse-power}}$.

Experiment 35.—The following particulars relate to a small Tangye double-acting steam engine, and Fig. 134 is an actual indicator diagram taken during a test. In this diagram a height of 1 in. represents a pressure of 40 lbs. per sq. in.

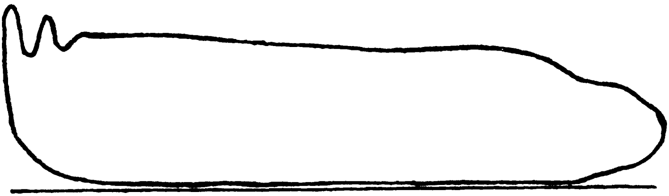


Fig. 134.

Engine stroke, 5 in. ; piston diameter, 4 in. ; piston-rod diameter, $\frac{3}{4}$ in. ; flywheel diameter, 25 in. ; deadweight on the end of the rope, 42 lbs. ; spring-balance reading, 5·5 lbs. ; revolutions per minute of the flywheel, 180.

Determine the indicated horse-power, brake horse-power, and the mechanical efficiency of the engine.

We must now return to study the indicator diagram a little more fully in order to be able to explain what has been happening when the diagram varies from what one would consider to be normal, and in Fig. 135 a few common faults which frequently develop are illustrated.

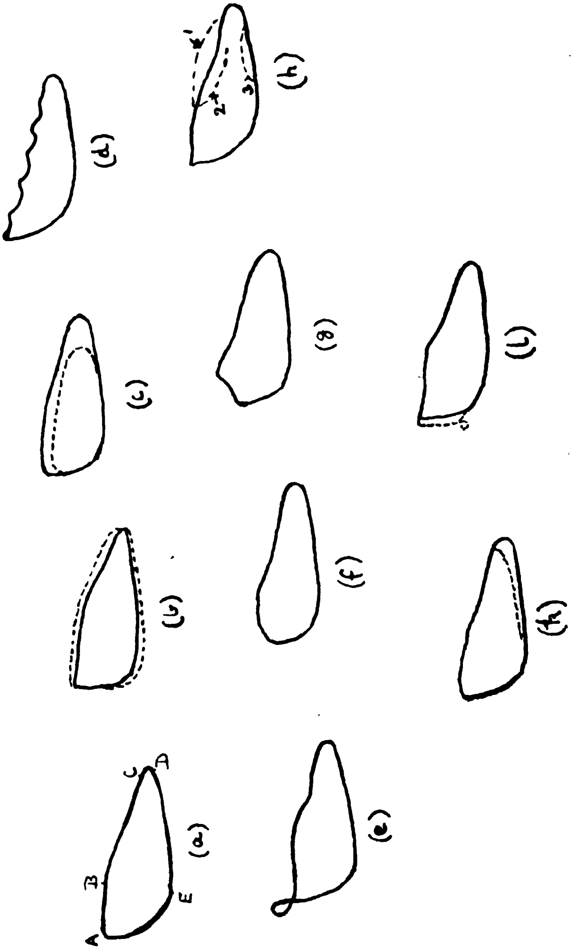


FIG. 135.

The diagram (*a*) represents a normal indicator diagram. A is the point of admission of steam to the cylinder, and AB is known as the steam or admission line. At B cut off takes place, then the steam expands along the line BC. When C is reached the exhaust port opens and the steam is released. The point D represents the beginning of the exhaust stroke, and the exhaust port closes when E is reached. As the exhaust port closes before the end of the stroke we have a quantity of steam left in the cylinder, and this is compressed from E to A.

In order to have a steady flow of steam from the boiler to the engine the pressure of the steam at the boiler must be greater than it is in the engine cylinder. If you examine a normal indicator diagram you will notice that as the piston moves forward in its stroke there is a slight drop in the steam pressure from the point of admission to the point of cut off, and this drop in pressure is known as " wire drawing." Wire drawing is much more noticeable in a high-speed engine than it is in a slow-running engine, and it results from the fact that the steam cannot enter the cylinder fast enough in order to maintain its maximum pressure until it is cut off.

Sometimes an error in an indicator diagram may be traced to the indicator itself, the diagrams (*b*), (*c*), and (*d*) in Fig. 135 representing cases in point. Assuming the full-line diagrams to be normal, the dotted-line diagram (*b*), which represents too great a pressure, would probably be caused owing to too much friction in the indicator piston and the pencil. The dotted-line diagram (*c*), in which the pressure indicated is too low, would very likely be caused by the stretching of the indicator cord which is attached to the drum and to the reciprocating part of the engine. The error in diagram (*d*), which is the stepped portion, would be caused if the indicator stuck at certain parts of the stroke. Sometimes an indicator diagram is too long, due to the inertia effects of the drum, but in most cases the error due to this cause can be neglected.

The diagrams (*e*), (*f*), and (*g*) (Fig. 135) are different from the normal diagram (*a*), but the irregularities here would not be the result of a faulty indicator. The loop in diagram (*e*) would very likely mean that admission of steam was late owing to the wrong setting of the eccentric, or the lead given to the slide valve may not have been sufficient. Occasionally the loop may be found on an indicator diagram when the load on the engine is small, and it will disappear as the load is increased. The fault in diagram (*f*) may also be caused owing to insufficient lead of the valve, but such a diagram would also result if there were a stoppage in the pipe leading to the indicator. This latter fault would also cause the error in diagram (*g*), but the rise in pressure would also mean that the steam port was not sufficiently opened at the beginning of the piston stroke.

The full-line diagram shown at (*h*) is normal, but sometimes this may vary and take the form as shown by the dotted lines 1, 2, and 3. The dotted curve 1 may mean that steam is leaking into the engine cylinder, perhaps owing to the surface of the valve chest or to the face of the slide valve itself not being plane. The dotted line 2 would also indicate steam leakage, but here it would be leaking past the piston owing to faulty piston rings. The dotted line 3 in this diagram is exaggerated and the error due to it is not very serious. Its presence would very likely mean that there was a small restriction in the exhaust port.

The dotted line in diagram (*k*) shows that the exhaust port is opened too late in the stroke, and as a result of this it will be late in closing on the return of the piston. As a result of this error the quantity of cushion steam remaining in the cylinder will be small, which in time will cause excessive wear on the crosshead and crankpin brasses. The loop formed in diagram (*l*) would result from water in the cylinder, the presence of which would be caused by condensation of cushion steam.

CYLINDER CONDENSATION

The walls of an engine cylinder will be cooler than the steam which enters, and as a result of this steam will be condensed. In order to maintain the power developed by the engine there must be an increase in the supply of steam, which in turn means that more coal must be burnt, and this must continue until the cylinder walls and steam are equal in temperature, when, of course, condensation will cease. As the engine continues to do its work the cylinder will receive heat in sufficient quantity so as to increase the temperature to a value greater than that of the steam, and the result of this will be that some of the water formed by the earlier condensation of steam will be re-evaporated, and it should be mentioned that the evaporation will be greater when the back pressure is low. Heat which has been abstracted from the cylinder to evaporate the water will cause the temperature of the cylinder to fall, and again on admission of steam there will be further condensation. In a single-cylinder engine any steam which is formed during the exhaust stroke will cause an increase in the back pressure so that less power will be developed, and the steam so formed will pass either to the atmosphere or to a condenser without performing any useful work.

When the difference in temperature is great between the cylinder and the admission steam the amount of steam condensed will also be great, and this being a disadvantage in the working of the engine, methods should be adopted in order to reduce the condensation to a minimum. One method of reducing condensation is to have a water separator fitted at the entrance to the engine cylinder, or a suitable lagging should be applied to the steam pipes, the steam being as dry as possible before entering the cylinder. If superheated steam is used it could part with some heat without condensation, this being an additional advantage of the use of superheated steam to that already mentioned, viz., that more work is done by expansion.

Steam which is compressed towards the end of the stroke will have its temperature raised so that some of its heat will be transmitted to the cylinder, and this will cause a reduction in the amount of steam condensed during the next admission.

Compound Engines

A compound engine is one in which we allow the steam to expand in two successive cylinders, such an engine being shown diagrammatically in Fig. 136.

Steam enters the small or high-pressure cylinder, and after doing its work is exhausted into the larger or low-pressure cylinder before finally being exhausted either into the atmosphere or into a condenser. In a compound engine a given quantity of steam will perform more work than in a single-cylinder engine, and, in addition, since expansion of steam takes place in the two cylinders the variation of temperature in each will be lowered, and this means less condensation.

Condensation is still further reduced in what are called triple-expansion engines, in which the steam works successively

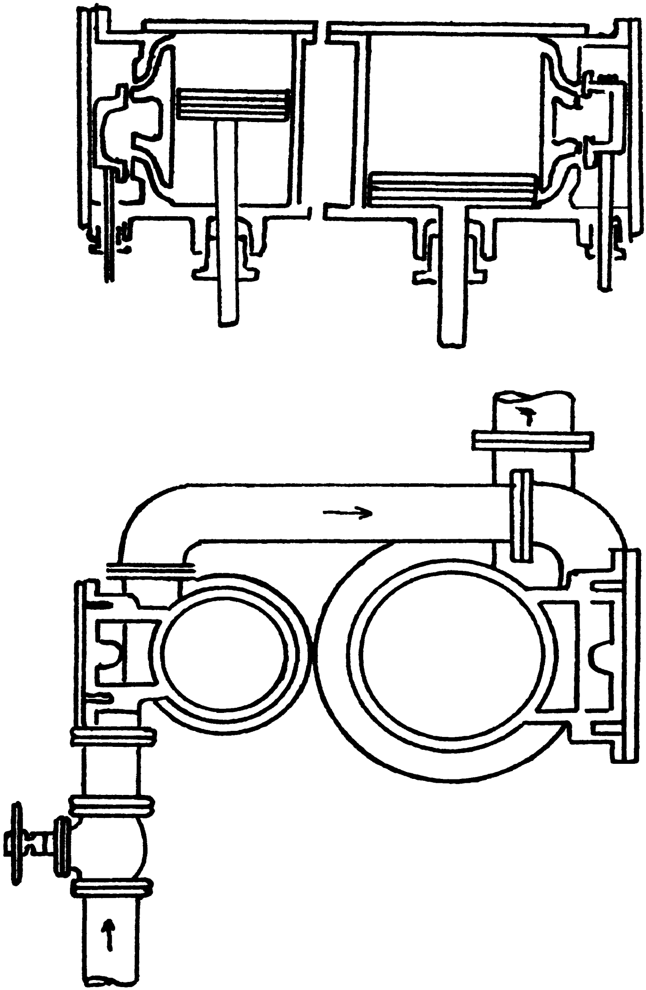


FIG. 136.

in the high-pressure, intermediate-pressure, and low-pressure cylinders.

Early in the present century, after carefully considering

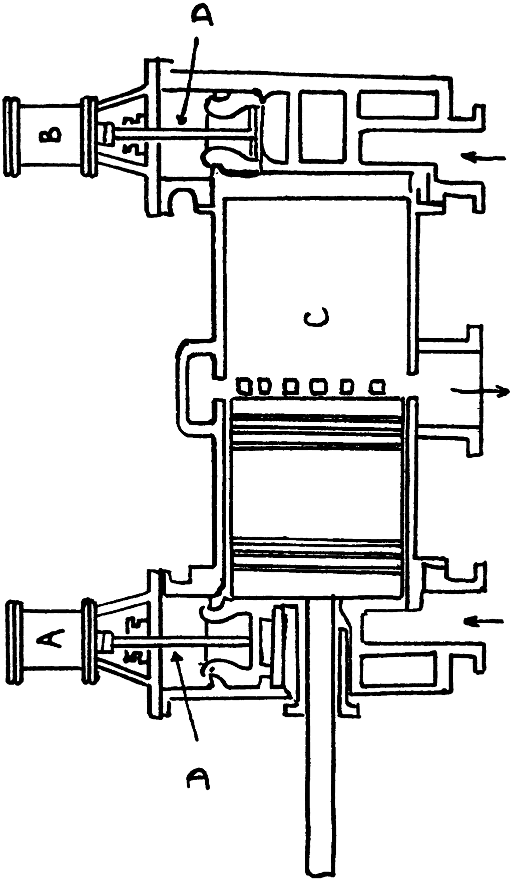


FIG. 137.

the subject, a German engineer named Stumph designed what is known as the " uniflow " or " straight-flow " engine in order to eliminate losses due to condensation of steam in an engine cylinder.

In the uniflow engine illustrated in Fig. 137 the idea is to reduce condensation of steam as far as possible, and also to eliminate the necessity for compounding. Drop valves at A and B, lifted alternately by the rods D, admit steam to the cylinder at opposite ends ; cut off takes place very early in the stroke, and after expansion the steam is exhausted through openings C placed round the centre of the cylinder. In the position as shown in Fig. 137 the valve A would lift and admit steam which would force the piston to the right, and the steam would pass through the exhaust ports C as soon as the left-hand end of the piston uncovered them. At a suitable instant valve B would lift and admit steam which would act on the piston towards the right, the cycle then being repeated.

In this type of engine condensation at admission would be reduced owing to the fact that the steam remaining in the cylinder on the return of the piston is very highly compressed, and some of the heat it receives during compression will be transmitted to the piston and cylinder ends, *i.e.*, the temperature difference at admission is very small. Owing to the high degree of compression in such an engine the cylinder will have to be much thicker than would be the case in an ordinary steam engine, but this drawback can be neglected when we consider its high steam efficiency.

Care and Management of Engines

The engineer in charge of an engine must exercise every care in order that his engine may work economically and yet efficiently. Before starting up the steam pipes should be thoroughly warmed, and when possible this should be done as soon as the boiler fire is started, so that hot air circulates through the pipes and condensation of steam, which would otherwise result, is avoided. This heated air can also be used to warm up the engine cylinder.

If steam is used for this warming-up process, it must be admitted gradually so as to avoid trouble due to unequal expansion of the various parts. In order to admit steam to both ends of the cylinder the engine should be turned by hand, and when the engineer is satisfied that condensation has ceased and that there is no water in the pipes, steam chest, or cylinder, the throttle should be almost fully opened so as to allow sufficient steam to enter to carry the engine past either dead centre. The flywheel will then carry the engine past the other dead centre, and the throttle should then be partially closed and the speed of the engine increased gradually by opening the throttle slowly.

All parts of the engine should be inspected at regular intervals and, when necessary, adjustments should be made. If any irregularities appear after the engine has been started, these should be noted and corrected as soon as possible. The lubricating system must always be kept in proper working order otherwise serious trouble will result. Ordinary lubricating oil may be satisfactorily used for journals and other bearings, but in the case of cylinders only thick cylinder oil will prove satisfactory. In order to obtain the best results with regard to lubrication the safest policy is to use only the oils which the makers of any particular engine recommend.

In closing down an engine the steam supply is cut off by closing the throttle, and it is advisable not to allow the engine to stop on either dead centre. In order to allow condensed steam to escape, drain cocks should be left open. Oil and moisture which may have gathered on bright parts of the engine should be wiped off when the engine has stopped, drip pans should be emptied and cleaned, and dust and dirt which may have settled on the engine-room floor should be swept up and removed.

THE STEAM TURBINE

The steam turbine is built in various sizes ranging from about 5 to over 50,000 B.H.P., and it has contributed very largely to the success we now enjoy of having power generated at a central station from which it is distributed for industrial and other purposes over a wide area.

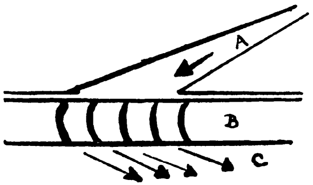


FIG. 138.

In its action the steam turbine converts a large proportion of the heat energy in the steam into kinetic energy by allowing it to expand in specially designed nozzles. Fig. 138 represents a De Laval steam turbine in which the expansion of steam takes place in the nozzle A. It then impinges on a number of blades B arranged round the circumference of the wheel, finally leaving at C. In such an arrangement we have the kinetic energy in the steam delivered as mechanical energy from a shaft on which the wheel is fixed. These fixed passages or nozzles arranged round the circumference of the wheel, together with the rotating vanes, form what is known as a turbine pair or stage, and problems connected with the design of such a stage have to receive very careful consideration in order to utilise as much as possible of the original energy in the steam.

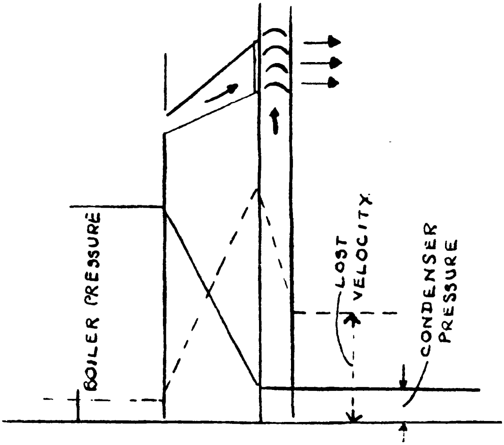


FIG. 139.

CLASSIFICATION OF STEAM TURBINES

The steam turbine may be classified under one of three general headings. First we have what is termed the impulse turbine in which the steam expands only in the fixed nozzles, the pressure in the moving parts being equal to that at the exit from the nozzle. The diagram in Fig. 139 represents a single disc mounted on a spindle, the blades being fixed round the circumference of this disc. The variation in pressure is shown by the full-line curve and that of the velocity of the steam by the dotted line. Notice that the steam pressure drops to condenser pressure before the steam passes through the blades. On the other hand, the velocity of the steam reaches its maximum in the nozzle and then drops during its passage through the blades, and in the case when two or more wheels are keyed to the shaft this process is repeated.

In the second type, known as a reaction turbine, the steam expands both in the nozzles and also in the moving blades, and in the latter case part of the heat energy in the steam is utilised in performing work on the wheel.

The third class of turbine is known as the impulse-reaction type, which is a combination of the above-mentioned types. In this type of turbine the high-pressure steam works by impulse and the low-pressure steam works by reaction.

A single disc rotor of an impulse turbine must rotate at a high speed in order to utilise as much as possible of the heat energy contained in the steam, but when running at high speeds trouble is likely to result owing to the effects of centrifugal force. Experiments on the whirling of shafts prove that it is essential to have a shaft of small diameter, and the bearings should be placed a considerable distance apart, or, in other words, a high-speed shaft should be flexible in order to eliminate trouble due to the effects of centrifugal force. The reason for this is because as the speed of a shaft increases the shaft will whirl and cause vibration. This will continue until a certain critical speed is reached when the centre of gravity of the system coincides with the centre of the rotating shaft and whirling ceases. In the case of a steam turbine this means that when the engine is started up the critical speed must be passed rapidly, otherwise failure may result. In cases where difficulties are likely to be encountered with regard to the actual construction of high-speed rotors it is possible to have an efficient machine running at slower speeds by velocity and pressure compounding. In this method we have a number of wheels containing the moving blades, and between the wheels are the guides or redirecting blades fixed to the casing of the machine. All the wheels are keyed to the same shaft and the stages work in series.

The Parsons Turbine

The Parsons turbine is an example of both the impulse and the reaction turbine, and is perhaps the most popular machine on the market. It consists of a fixed part (the stator) and a moving part (the rotor), and it is represented diagrammatically in Fig. 140. Steam passes first through the fixed blades and then through the moving blades, but owing to the fact that energy has been given to the moving blades the velocity of the steam on leaving these blades will be less than it is on leaving the fixed blades. After leaving the first set of moving blades the second set of fixed blades will redirect the steam on to the second set of moving blades, and this action may be repeated for fifty stages or even more. Finally the steam will be sent either into the atmosphere or into a condenser.

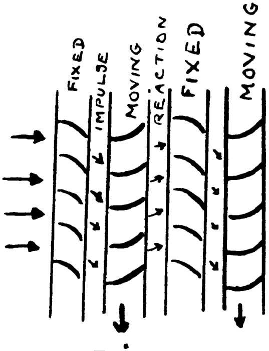


FIG. 140.

The motion of a steam turbine is rotary, so that there is no such term as indicated horse-power, and for the same reason a flywheel is not necessary. For the generation of electrical energy and also in marine work the steam turbine has proved very successful. In electrical work the work given out by a generator is often stated as the work done on the engine shaft, and the overall efficiency of a steam turbine plant is the ratio

$$\frac{\text{Shaft horse-power or electrical horse-power}}{\text{Energy supplied in the steam}}.$$

A steam turbine can work satisfactorily for considerable periods, but it is advisable to overhaul the plant at least once a year, when all parts should receive a very careful examination. From the point of view of general efficiency, perhaps, the blading may be regarded as the most important part of the machine. The blades of a turbine will deteriorate through two causes, erosion due to wear and corrosion due to chemical action, and in the latter connection it should be mentioned that if the blades are worn the weakening effects of corrosion will spread rapidly. When a turbine is shut down all parts should be thoroughly cleaned, and special attention should be given to the lubricating system.

ELEVENTH SET OF EXAMPLES

1. Give a diagram of a simple steam engine connected to a Lancashire boiler. Show on the diagram all the points at which transmission or conversion of energy takes place and describe the nature of each transmission or conversion.

U.L.C.I.

2. The indicated horse-power of a double-acting steam engine may be determined by the formula $\text{H.P.}=\frac{2\ \text{PLAN}}{33000}$. Explain how this formula is derived.

3. Explain the action of a flywheel and governor in regulating the speed of an engine.

4. Sketch in outline an eccentric, and describe briefly how the slide valve of a steam engine is operated.

U.L.C.I.

5. The mean effective pressure of the steam in a double-acting steam engine is 30 lbs. per sq. in. The area of the piston is 77 sq. in., the crank is 9 in. long, and the engine runs at 150 revs. per min. Determine (*a*) the work done per stroke, (*b*) the indicated horse-power.

6. Explain the meaning of the terms "steam lap" and "lead of a slide valve," and "angle of advance of an eccentric."

The travel of a slide valve is $4\frac{3}{4}$ in., the steam lap is $1\frac{1}{8}$ in., and the lead is $\frac{1}{16}$ in. Find the angle of advance at which the eccentric must be set. Find also the crank positions at admission, cut off, release, and compression.

7. The cylinder of a simple steam engine is $10\frac{1}{2}$ in. diameter and its stroke is 15 in. Compare the work done in the cylinder per stroke when the engine is running at 180 revs. per min. and the average steam pressure is 60 lbs. per sq. in. with the work done when the engine is running at 150 revs. per min. and the average steam pressure is 40 lbs. per sq. in. Compare also the horse-power developed in the two cases.

U.L.C.I.

8. From the diagram given in Fig. 141 determine the indicated horse-power of the engine. Diameter of cylinder, 25 in.; length of stroke, 5 ft.; revolutions of crankshaft, 65 per min.; pressure scale, $\frac{1}{50}$. U.L.C.I.

9. Find the diameter of the cylinder and the length of the stroke of an engine required to satisfy the following conditions :—

Mean effective pressure of steam=70 lbs. per sq. in.
Diameter of cylinder=length of crank.
Speed of crankshaft=60 revs. per min.
Brake horse-power=720.
Mechanical efficiency=80 per cent. U.L.C.I.

10. Steam enters the cylinder of an engine at a pressure of 80 lbs. per sq. in. absolute and is cut off at 0·5 stroke. Assuming a back pressure of 17 lbs. per sq. in., draw to scale a hypothetical diagram for one stroke, and find the theoretical mean effective pressure of the steam.

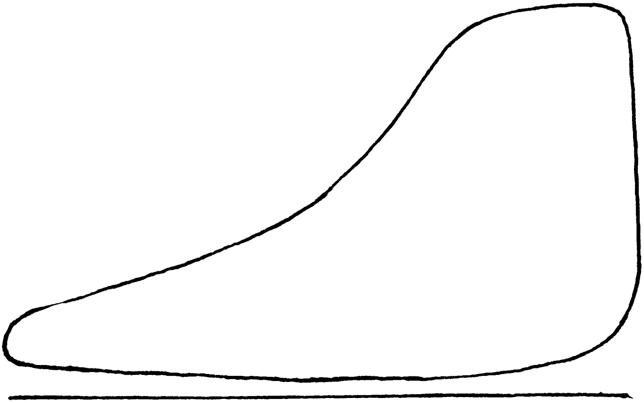


FIG. 141.

Indicate by dotted lines how the theoretical diagram would be modified in practice. U.L.C.I.

11. The steam lap of a slide valve is $1\frac{1}{2}$ in., the maximum opening to steam is 1 in., and the angle of advance of the eccentric is 27°. Determine the lead given to the valve.

12. A double-acting single-cylinder steam engine is to develop 50 I.H.P. at a speed of 120 revs. per min. Steam pressure at admission, 65 lbs. per sq. in. absolute ; cut off, 0·4 stroke ; stroke, 18 in. Assuming a back pressure of 16 lbs. per sq. in. absolute and a diagram factor of 0·85,

find the diameter of the cylinder. What would you expect the brake horse-power to be? U.L.C.I.

13. Describe, with outline sketches, the general features of any steam turbine, and explain the action of the steam in producing mechanical work as it passes through the turbine.

CHAPTER XIV

THE INTERNAL COMBUSTION ENGINE

The internal combustion engine (so named because combustion of the working substance takes place inside the engine cylinder) may be classified according to what type of fuel is used as the source of power. For example, such an engine may work on coal-gas or producer gas, another type would use petrol or paraffin in a vaporised form, while a third type would use heavy oil in a liquid state.

The first type to be developed was the gas engine, and in 1878 one was designed which would develop 3 B.H.P. Four years later a larger engine was constructed which would develop 20 B.H.P., and the horse-power available was increased to over 200 by 1898. From that date progress continued, and developments have been very rapid since the beginning of this century. The first patents were taken out for the Diesel oil engine in 1892, but progress generally with this type of engine has, until recently, been much slower than was the case of the gas engine.

Marine engineers very soon recognised the fact that certain economies would be effected by using the internal combustion engine as a means of ship propulsion, and in this connection successful results have been attained with the Diesel engine using crude oil. From the commercial point of view a very important consideration is cost, and in this connection the Diesel engine is much more economical than the steam engine. In addition, there will be a saving in wages because stokers will not be required. Another important item which has a large monetary value is the saving in space which will be effected owing to the fact that for a given voyage much less oil will be needed than would be necessary in the case of coal. On the other hand, if oil occupied a large space a longer voyage could be undertaken without having to refuel.

Considering the general trend of the fuel question, it would appear that in the near future, both as a source of power and also for transport, the oil engine will be in great demand because of the economies which can be effected by its use. In time all parts will be standardised, which will be more economical both from the manufacturer's and user's points of view.

If coal-gas or producer gas is the working substance for an internal combustion engine, the engine may work on either the Otto or four-stroke cycle or the Clerk or two-stroke cycle. An engine using petrol in the form of a vapour will also work on either of the above-mentioned cycles, but the Diesel engine, which uses oil in liquid form, works on what is known as the Diesel four or two stroke cycle.

A gas engine working on the Otto or four-stroke cycle is represented in Fig. 142, A being the inlet valve through which a suitable mixture of gas and air is admitted to the cylinder, B being the exhaust valve through which the spent mixture is exhausted. The four strokes of this cycle are numbered 1 to 4 in the diagram and are as follows : First stroke, during which the piston moving outwards draws in a suitable mixture of air and gas, the stroke being known as the suction stroke. In the case of an engine working on petrol or paraffin oil the liquid is vaporised before being admitted to the cylinder during the suction stroke. (Inlet valve A open, exhaust valve B closed during this stroke.) On the return of the piston we have the second or compression stroke, during which the mixture is compressed to a very high degree. (During this stroke both valves are closed.) At a suitable point, near the end of the second stroke, the compressed mixture is fired, the pressure of the mixture rises rapidly, and we have the third or working stroke. (Both valves closed.) During the fourth stroke of the piston the spent gases are expelled from the cylinder, the stroke being known as the exhaust or scavenging stroke. (Inlet valve A closed, exhaust valve B open during this stroke.) The above cycle is then repeated.

From the above description of the four-stroke cycle we can see that there is only one working stroke out of every four strokes of the piston or for every two revolutions of the flywheel, and for that reason the flywheel of a gas engine has to be very heavy in order to obtain sufficient energy from one stroke to carry the piston through the remaining three strokes.

The full-line diagram in Fig. 143 represents the ideal or hypothetical indicator diagram for a gas engine working on

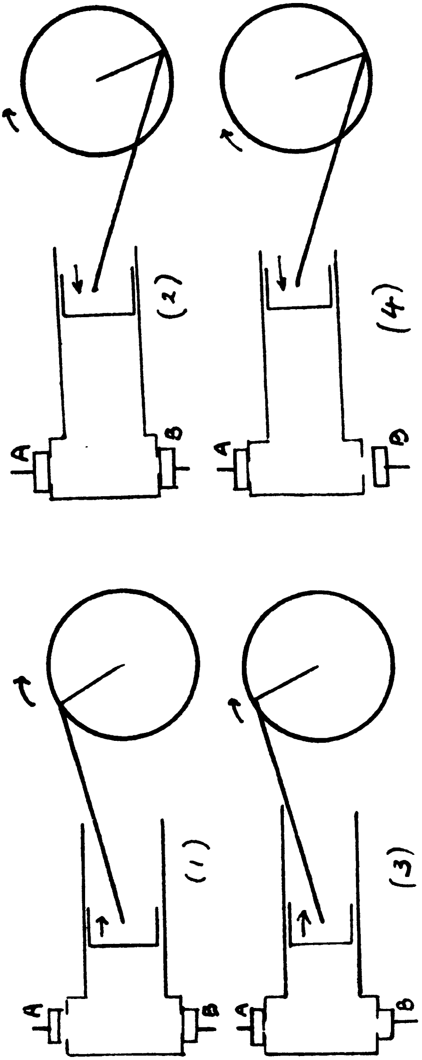


FIG. 142.

the Otto cycle. The suction stroke, theoretically at atmospheric pressure, is represented by AB. Compression follows along BC, and at C, ignition being instantaneous, we have the rise in pressure CD. The third stroke is represented by DE, and finally, again at atmospheric pressure, the exhaust stroke is along BA. When ignition takes place, as illustrated at C, the consequent rise in pressure CD takes place at constant volume, and for this reason this ideal cycle is often referred to as the constant volume cycle. The dotted-line diagram in Fig. 143 represents, roughly, the type of indicator diagram which would be obtained in practice.

In order that a gas engine should run efficiently it is very important that the valves should open and close at the correct moment. As an example, consider the ignition point. The hypothetical indicator diagram shows this to be instantaneous and at the end of the compression stroke, but in practice it would happen just before the end of the second stroke in order to allow the maximum pressure to be reached at the beginning of the third or working stroke. In doing this we are said to advance the point of ignition, but we must not advance it too far otherwise we shall have what is called a back-fire. The timing of the valves may be done by means of a diagram similar to that shown in Fig. 144.

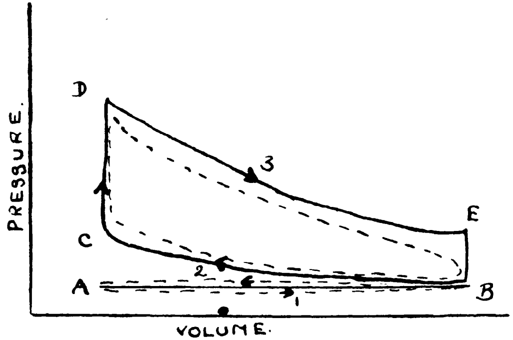


FIG. 143.

In this diagram PQ represents the stroke of the piston, and the two circles each represent a revolution, the outer circle being the first revolution and the inner circle the second.

The radial lines represent the crank position at the various points considered. As constructed this valve-timing diagram would mean that the inlet valve would open when the crank is at A, which is 3° before the beginning of the suction stroke. The valve would remain open until the crank had reached the position B, which is 45° past the outer dead centre, when it would close. When the crank reaches the position C, which is 15° before reaching the inner dead centre on the compression stroke, ignition would take place. As the crank reaches the point D on the third stroke, and 55° before the outer dead centre, the exhaust valve would open, and would not be closed until the point E had been reached, which in this case is 2° past the inner dead centre.

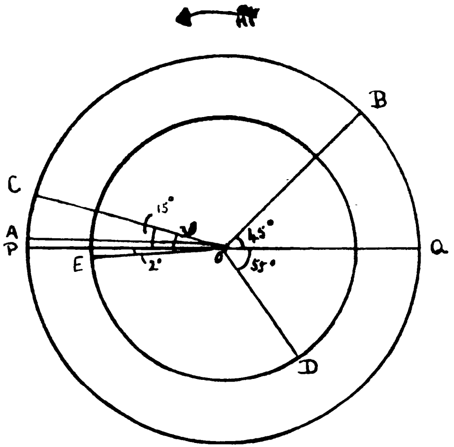


FIG. 144.

We have seen that the point of ignition must be just before the end of the compression stroke, and it has already been mentioned that if this point is too far advanced the result will be a back-fire, which in the case of a petrol engine will be dangerous, especially if the back-fire takes place through the carburettor. On the other hand, if the timing for ignition is too late it will mean that the flame will not have time to pass through the mixture completely before the piston commences its third stroke. A result of this will be to cause overheating of the cylinder owing to the flame having to travel down the cylinder behind the piston instead of being confined to the combustion chamber at the head of the cylinder. Another result will be loss of power developed by the engine owing to the flame acting on a mixture which is losing compression.

Before leaving this subject relating to the action of the flame on the mixture of gas and air there is another point which may be mentioned. In practice it has been proved that heat is often evolved during the expansion stage, and this is termed the " after burning " of the gas. As you know, certain chemical reactions take place at a fixed temperature, and in the present case it is thought that perhaps the temperature due to ignition is too high for complete combustion at the beginning of the stroke, but that it may be completed during expansion when, of course, the temperature falls.

Some readers of this book may possess a motor cycle or a car, and they know from experience that they can obtain a more efficient working of their engine with a weaker mixture than they can with a strong mixture. One reason for this is because in a strong mixture, *i.e.*, when there is too much gas for a given quantity of air, there will not be sufficient air for complete combustion of the gas, so that some of the gas may be sent into the exhaust without performing its work, and this means a low efficiency. On the other hand, with a weaker mixture there will be sufficient air for the complete combustion of the gas, and this will result in a higher efficiency. Also, the higher temperature reached during the combustion of a strong mixture will manifest itself in the form of an overheated cylinder, which, as you probably know, is not conducive to efficient working. Finally, the specific heat of a gas is not constant—it increases with the temperature, and this means that the supply of heat will be greater in proportion to the corresponding temperature and pressure, and if the pressure is low the efficiency will be low also.

At the present stage of our work we are not in a position to discuss all the tests which have to be carried out in order that a gas engine may satisfy a purchaser, but the student will be expected to be able to make a test to determine the mechanical efficiency of such an engine.

In performing this test the method is the same as in the case of the steam engine discussed in the previous chapter, *i.e.*, we require the ratio $\frac{\text{brake horse-power}}{\text{indicated horse-power}}$.

The method of determining the brake horse-power is exactly the same as in the case of the steam engine, but for the indicated horse-power we require the number of explosions per minute instead of the revolutions per minute. For example, if P lbs. per sq. in.=pressure of the gas in the cylinder obtained from an indicator diagram, A=area of piston in square inches, L=length of stroke in feet, and E=explosions per minute, then the indicated horse-power will be $\frac{PALE}{33000}$.

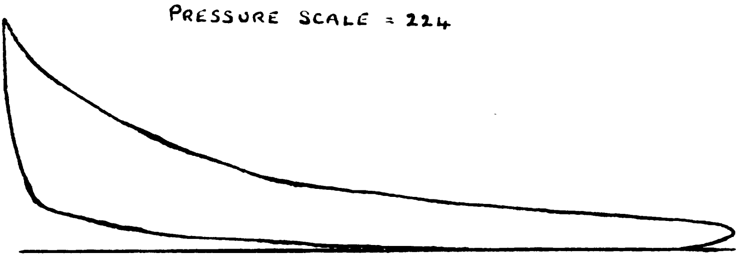


FIG. 145

EXPERIMENT 36.—The following particulars relate to a Tangye gas engine working on the Otto cycle, and Fig. 145 is an actual diagram taken during a test :—

Stroke, 18 in. ; piston diameter, 11 in. ; flywheel diameter, 6 ft.

Deadweight on flywheel, 172 lbs. ; spring-balance reading, 6·5 lbs.; revolutions per minute, 150; explosions per minute, 60.

Determine the mechanical efficiency of the engine.

We must now briefly consider the action of a suction gas producer in which the gas which is used for the working of a gas engine is generated. This apparatus is illustrated diagrammatically in Fig. 146 and consists of two main parts, A, in which the gas is produced, and B, called a scrubber, in which the gas is cleaned before passing to the gas engine cylinder.

On the suction stroke of the gas engine piston, air is drawn in underneath the fire-grate and passes upwards through A. Vigorous combustion of the coal or coke takes place in the lower part of the apparatus, but in the upper part the fuel is only allowed to burn slowly, so that in passing through the mass of fuel the CO_2 which is formed in the lower part turns to CO, and this gas is used in the engine cylinder. At the top of the producer there is a vaporiser, and the steam formed is led along the steam pipe shown and is admitted underneath the fire-grate. As soon as this steam comes into contact with the incandescent carbon there will be a reaction, which is given by the equation $C+H_2O=CO+H_2$, and during this reaction each pound of carbon will give out, roughly, 4,500 B.Th.U. This loss of heat from the carbon is a decided advantage because it means that the temperature of the producer will be lowered. Also, the hydrogen which is set free passes along with the CO and adds to the heating value of the gas. It should be mentioned that the above reaction takes place at a temperature of 1,800° F. and above, so that the higher the temperature the greater the efficiency of the producer.

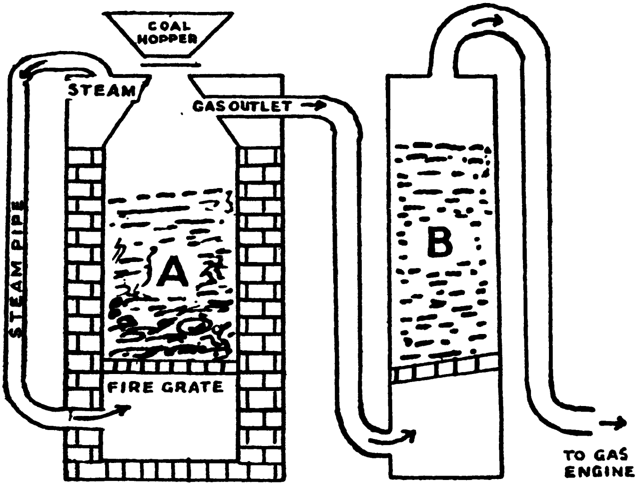


FIG. 146.

Fig. 147 shows an ordinary suction gas producer made by Messrs Tangye Ltd., of Birmingham, in which gas is produced from anthracite, coal, or coke, and Fig. 148 shows one type of engine which works very successfully on the gas produced. In the report of a test carried out with this type of producer and engine it is stated that the fuel consumption is extremely low and that the thermal efficiency of the plant was 26·9 per cent., which result is considered highly satisfactory.

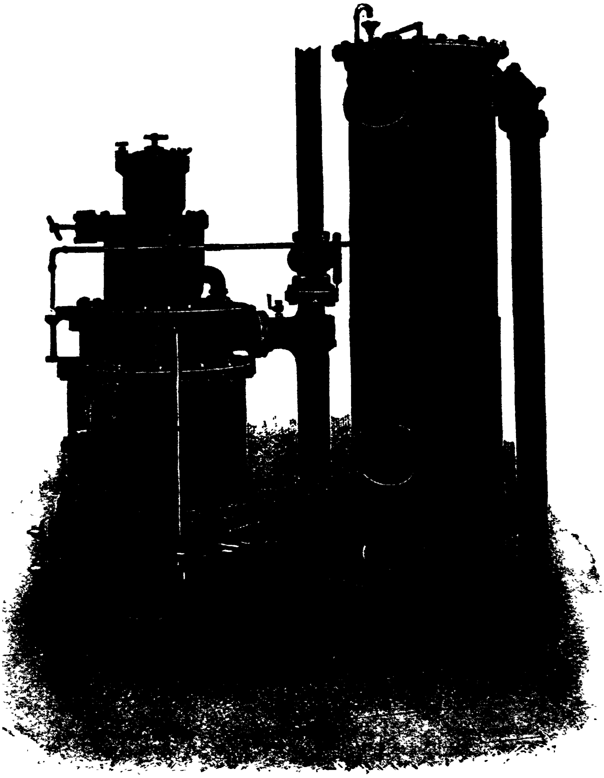


FIG. 147.

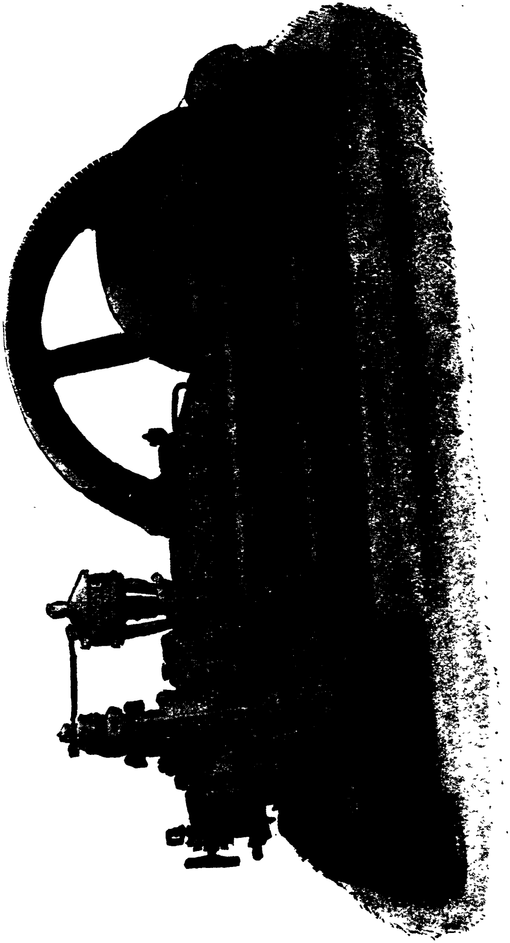


FIG. 148.

THE CLERK OR TWO-STROKE CYCLE

In an engine working on this cycle, named after Sir Dugald Clerk, we have one working stroke for every revolution of the flywheel, and for some classes of work it possesses advantages which cannot be claimed by an engine working on the four-stroke cycle. For example, a smaller engine would be required to develop a given power working on the two-stroke cycle than would be required if working on the four-stroke cycle, or we can say that an engine working on the Clerk cycle will develop nearly twice the power as the same size of engine working on the Otto cycle, provided, of course, that the revolutions per minute are the same in the two cases. In marine engineering it has been found that a higher propeller efficiency can be obtained at slow speeds than would be the result at high engine speeds. In the case of the internal combustion engine this means that the engine working on the two-stroke cycle is more efficient than the four-stroke cycle engine because the same power will be developed at half the speed. Another advantage of the two-stroke cycle engine is the fact that the turning effort on the shaft will not be so irregular.

The two chief disadvantages of the Clerk cycle engine are that the gas consumption is greater than in the Otto cycle engine, which means that there will be a tendency for the engine cylinder to become overheated, and, secondly, the wear and tear on the moving parts are much greater than is the case in the latter type.

The action of the two-stroke cycle is illustrated diagrammatically in Fig. 149. Just before the beginning of the working stroke the valve V opens to admit the gas into the cylinder. The gas is highly compressed, and when ignited acts on the piston, forcing it outwards, and so giving the working stroke. After travelling a given distance the piston will uncover the exhaust port E in the cylinder wall and so the spent gas will be exhausted. Further movement of the piston will then uncover the port S, known as the scavenging air port, which will thus enable air at atmospheric pressure to enter the cylinder and expel any gas which remains in the cylinder, and at the same time the cylinder will be charged with pure air. As the piston returns it will cover the port S and then the exhaust port E, after which the air will be compressed, when it will be ready for the next supply of gas just before the end of the compression stroke. The gas is then ignited and we have the working stroke, and the cycle is repeated.

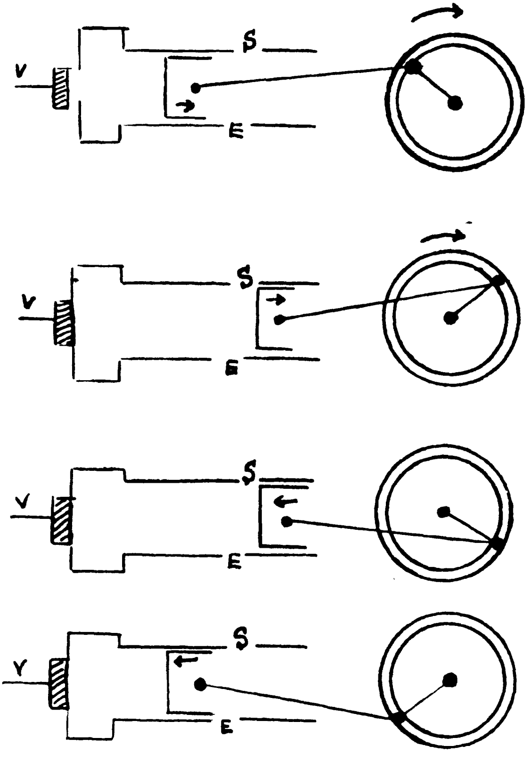


FIG. 149.

In some engines valves are placed in the cylinder head to admit scavenging air instead of using the port S, as described above, and in such cases the valve will be timed to close just after the piston covers the exhaust port on the compression stroke. With such an arrangement the cylinder will be charged with a supply of air at a pressure above atmospheric, and we shall therefore obtain a greater quantity of air, which will allow a greater quantity of gas to be burnt, and so we shall have greater power developed in the engine cylinder, the result being known as supercharging.

Fig. 150 represents an indicator diagram from an engine working on the two-stroke cycle. When the point *a* is reached the exhaust port will be uncovered, and from *a* to *c* and back to *b* we shall have exhaust, scavenging, and then the recharging of the cylinder with a fresh supply of air.

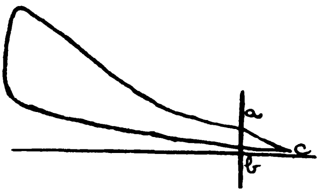


Fig. 150.

The Diesel Four-stroke Cycle

The Diesel engine works on crude oil, which is admitted to the engine cylinder at the correct moment in atomised form through a special fuel injection valve. The diagram (Fig. 151) represents the Diesel four-stroke cycle, and it will be noticed that there are three separate valves, A, F, and E, these being respectively the air, fuel, and exhaust valves.

During the first stroke of the piston, the suction stroke, air is drawn into the cylinder at atmospheric pressure, the valves F and E being closed. On the return or compression stroke all valves are closed, and owing to the fact that in this type of engine the clearance volume is very small we have a much higher degree of compression than we have in the Otto cycle. Near the end of the compression stroke the fuel valve F will open and oil will be injected into the cylinder. Owing to the high compression the oil will be ignited immediately and we have the third or working stroke. Finally, on the fourth stroke of the piston, the exhaust valve E will open and the spent fuel will be exhausted.

The ideal or hypothetical indicator diagram for this cycle is illustrated in Fig. 152. The line AB represents the suction stroke; compression takes place along BC, and when the oil is ignited constant pressure is exerted along CD, after which expansion occurs along DE and exhaust along BA. Owing to the constant pressure along CD this cycle of events is referred to as the constant pressure cycle. The dotted-line diagram in Fig. 152 shows how the ideal case is modified in practice.

In comparing the main essentials of the three types of

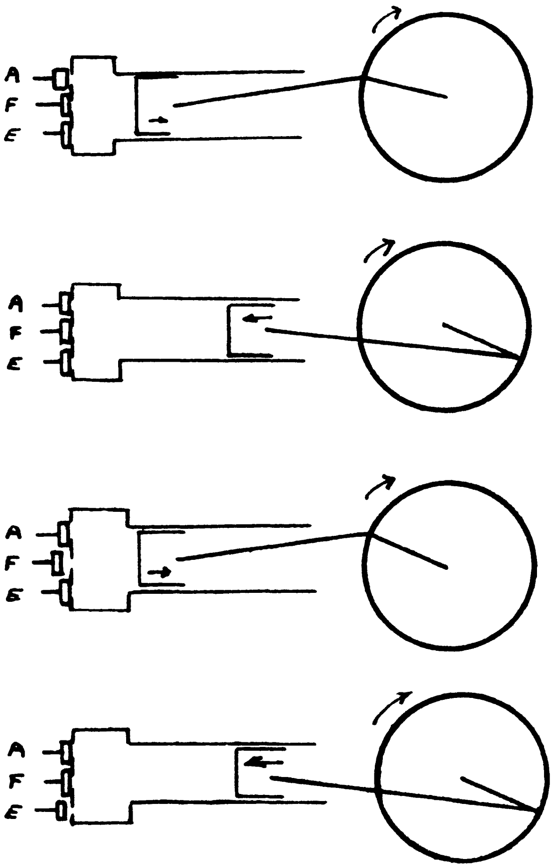


FIG. 151.

internal combustion engines working on the four-stroke cycle the following points may be mentioned : In the gas and petrol engines we have either gas and air in one type or petrol vapour and air in the other type drawn into the cylinder during the first stroke and compressed during the second stroke, but in the Diesel engine pure air only is drawn in and compressed, and in this case there is no danger due to pre-ignition. Also, the compression pressure of the gas engine is nearly twice as great as that in the petrol engine, but that of the Diesel engine is more than five times as great, and again the advantage of the latter type is that ignition takes place, due entirely to the heat of compression. The compression temperature in the gas engine is roughly 570° F., in the petrol engine it is roughly 350° F., but in the Diesel engine it may be as high as 950° F. If we take into account the quantity of fuel used

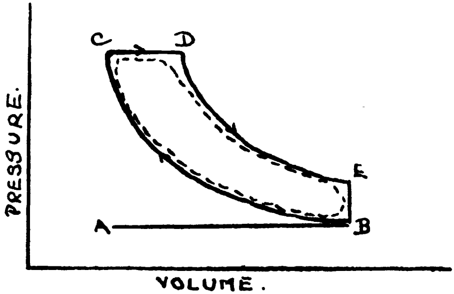


FIG. 152.

per brake horse-power hour and the heating values of the fuels, we shall find that the average thermal efficiency of the gas engine is about 26 per cent., that of the petrol engine is about 22 per cent., while that of the Diesel engine is as high as 33 per cent., or even higher.

Example 1.—A gas engine develops 30 I.H.P. and 25·5 B.H.P. for a gas consumption of 720 cub. ft. per hour, the calorific value of the gas being 480 B.Th.U. per cub. ft. Determine the mechanical efficiency and the thermal efficiency, the latter on both the indicated horse-power basis and on the brake horse-power basis.

$$\text{Mechanical efficiency} = \frac{\text{brake horse-power}}{\text{indicated horse-power}} = \frac{25\cdot5}{30}$$

$$= 85 \text{ per cent.}$$

Gas used by the engine per minute$=\frac{720}{60}=12$ cub. ft.

Energy supplied by the gas per minute$=12\times 480\times 778$ ft.-lbs.

Energy given out per minute on indicated horse-power basis $=30\times 33{,}000$ ft.-lbs. Therefore indicated thermal efficiency

$$=\frac{\text{energy given out}}{\text{energy supplied}}=\frac{30\times 33000}{480\times 12\times 778}=23 \text{ per cent.}$$

Thermal efficiency on brake horse-power basis

$$=\frac{25\cdot 5\times 33000}{480\times 12\times 778}=18\cdot 78 \text{ per cent.}$$

TWELFTH SET OF EXAMPLES

1. A gas engine works on the "Otto" cycle. Explain the meaning of this term. Find the indicated horse-power of a gas engine having a cylinder diameter of 8 in. and a stroke of 15 in. Mean effective pressure, 80 lbs. per sq. in.; revolutions per minute, 150; number of explosions per minute, 60. U.L.C.I.

2. Describe the action of a two-stroke cycle gas engine and explain the advantages and disadvantages of this type of engine.

3. A gas engine works on the Otto cycle. What should be the mean effective pressure on the piston during the working stroke for the engine to develop 25 H.P. when the cylinder is 11 in. diameter; stroke, 17 in.; revolutions per minute, 200, and explosions per minute, 85? U.L.C.I.

4. Describe the four-stroke cycle of a gas engine and sketch a typical indicator diagram. The area of a gas-engine indicator diagram was measured by a planimeter and found to be 1·01 sq. in., and the length of the diagram was 3·35 in. Find the indicated horse-power of the engine having given the following data: Diameter of cylinder, 9 in.; stroke, 15 in.; revolutions per minute, 170; explosions per minute, 70; strength of spring in indicator, 160 lbs. per inch movement of the indicator pencil. U.L.C.I.

5. Describe by means of a diagram the Otto cycle of operations in a gas engine.

A gas engine working on the four-stroke cycle has a cylinder 15 in. in diameter and a piston stroke of 22 in. The mean effective pressure of the gas during a working stroke is 75 lbs. per sq. in. The engine runs at 205 revs. per min., and the number of explosions per minute is 90. Find the indicated horse-power of the engine. U.L.C.I.

6. Assuming the mechanical efficiency of the gas engine in the previous example to be 80 per cent., determine the brake horse-power.

7. Fig. 153 shows an indicator diagram taken during a trial of a gas engine in which the cylinder diameter was $6\frac{1}{2}$ in. and the piston stroke 12 in.

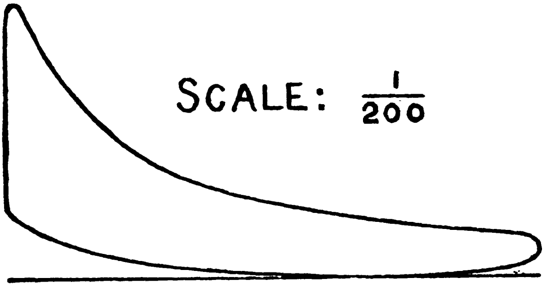


FIG. 153.

The following particulars refer to the trial :—

Revolutions per minute of the flywheel, 260 ; explosions per minute, 130 ; scale of indicator spring, $\frac{1}{200}$; gas used per hour, 330 cub. ft. ; calorific value of the gas, 380 B.Th.U. per cub. ft.

Determine the mean effective pressure of the gas, the indicated horse-power, and the thermal efficiency of the engine on the indicated horse-power basis.

8. The calorific values in centigrade heat units of coal, coal-gas, and kerosene are as follows :—

1 lb. of coal, 8,080.

1 cub. ft. of coal-gas, 260.

1 lb. of kerosene, 11,000.

Using the above values, determine the efficiencies of :

(*a*) A steam engine using 2 lbs. of coal per B.H.P. hour.
(*b*) A gas engine using 26 cub. ft. of coal-gas per B.H.P. hour.
(*c*) A Diesel oil engine using 0·56 lb. of kerosene per B.H.P. hour.

ANSWERS TO THE NUMERICAL EXAMPLES

First Set

1. 3.30 P.M.; 32 miles from A., 18 miles from B. **2.** 60 m.p.h. or 88 ft. per sec. **3.** 4 mins. **4.** 40·75 m.p.h. at an angle of 27·5° to the 20 m.p.h. velocity. **5.** 24 ft. per sec. **6.** $\frac{1}{2}$ mile. **7.** 12 secs.; 108 secs. **8.** 264 ft.; 396 ft. **9.** $\frac{121}{9}$ ft. **10.** 33 ft./sec.^{2}; 66,000 yds./min.^{2}. **11.** $68\frac{1}{16}$ ft. **13.** 1·45 ft./sec.^{2} at 30° to the vertical. **14.** 620 ft. **15.** 1 sec. **17.** 120 secs.; $\frac{11}{15}$ ft./sec.^{2}.

Second Set

1. 20 secs. **5.** 600 units; 30 grm. **7.** 137,984 units; 59·2 secs. **8.** 43·2 lbs. **9.** 3·24 ft. **11.** 31 m.p.h. **12.** $564\frac{2}{3}$ lbs.

Third Set

1. 6·8 (approx.). **3.** 540 ft.-lbs.; 324 ft.-lbs. **4.** 468·75 ft.-lbs.; 1406·25 lbs. **6.** 32,000 ft.-lbs. **8.** 1268·2. **9.** 76·13 tons. **10.** 754·3 ft. per min.; 1·1 H.P. **11.** 7 (approx.). **12.** (*a*) 0·72; (*b*) 1,120; (*c*) 8. **13.** I., 72°; II., 0·0175 in.

Fourth Set

1. (*a*) 1,900 lbs., 2,000 lbs.; (*b*) 3 ft. $10\frac{2}{3}$ in. **3.** 2 ft. from 30 lbs. weight; 60 lbs. **4.** B=18 lbs.; C=4 lbs. **5.** 6 tons; 1 ton. **6.** 3,808 lbs.; 3,136 lbs. **7.** $6\frac{2}{3}$ ft. **8.** 53°; 243 lbs.; 440 lbs. at 34° to the horizontal. **9.** $18\frac{4}{15}$ in. from 6 lbs. weight. **10.** 150 lbs. **11.** A=$1\frac{3}{16}$ tons; B=$1\frac{13}{16}$ tons.

13. **AF=DK=4·7** tons compression.
BG=HC=3·45 ,, ,,
FG=HK=1·1 ,, ,,
EF=EK=4·2 ,, tension.
GH =2·4 ,, ,,

15. **DC=EC=FC=0·6** ton tension.
AD=BF=0·3 ton compression.
DE=EF=0·6 ,, ,,

Fifth Set

1. 0·2 ; 5·4 lbs. **2.** 30 ft.-lbs. **3.** 0·448. **5.** 0·08 ; 4 ft.-lbs. **10.** 3·5 ; 30 lbs. ; 70 per cent. **11.** 3 lbs. **12.** 20. **13.** (*a*) E=0·196W+2·024 ; (*b*) 8·688 ; 3·91 ; 24·4 per cent. **14.** 352 ; 3·54 lbs. ; 3·7 lbs.

Sixth Set

1. 159·15 lbs. per sq. in. ; 0·000625. **2.** 2·026 in. **4.** 10,220 lbs. or 4·58 tons. **5.** Stress=16,000 lbs. per sq. in. ; strain, $\frac{1}{1600}$; modulus of elasticity, 25,600,000 lbs. per sq. in. ; **7.** Stress=9,550 lbs. per sq. in. (approx.) ; elongation=0·0764 in. **8.** 2 in. **9.** 119 (approx.) **10.** 179. **11.** 1·5 in. (approx.). **12.** 1·26 in. (approx.). **13.** 6. **14.** (*a*) Stress, 22,280 lbs. per sq. in. ; (*b*) strain, 0·0007427 ; (*c*) elongation, 0·4456 in.

Seventh Set

1. 33·8 ft. **2.** 11·3 tons (approx.). **3.** 4·17 ft. (nearly). **6.** 2·625 (nearly). **7.** 0·28 lb. per cub. in. ; 0·78 (nearly). **8.** 3 lbs. **9.** 0·6 (nearly). **10.** 0·6124 ; 0·6061 ; 0·6198 ; average =0·6128. **11.** 16 ft.

Eighth Set

1. (*a*) 86°, 194°, 255·2°, 392°, 680°, 14°, −79·6°, −148° ; (*b*) 5°, 25°, 56°, 102°, 160°, −6°, −23°, −80° ; (*c*) −40°. **2.** 1,710° C. ; 1,600° C. ; 1,232° C. ; 316° C. ; 2·2° C. **3.** 30·018 in. **4.** 0·023 in. **6.** 0·000536. **7.** −74·6° C. **9.** $\frac{1}{120}$. **10.** 77·3° C. ; 1661·1 lbs. per sq. in. **11.** 293° C. **12.** 104,900 cub. ft. **13.** 93° C. **14.** 151·5° C.

Ninth Set

2. 0·031. **5.** 6·25 grm. **6.** 2736·6 calories. **7.** 1022·061 B.Th.U. **10.** 8,712 C.H.U. **11.** 990,000 ; 1,273 B.Th.U. **12.** 653,500 ; 668·2. **13.** 620° C. **15.** $\frac{1}{4}$ hour.

Tenth Set

2. 8,971 C.H.U. ; 12·296 lbs. **3.** 18,210 B.Th.U. per lb. **9.** 69·61 per cent. **10.** 11·69 lbs.

Eleventh Set

5. (*a*) 3,465 ft.-lbs.; (*b*) 31·5. **6.** Angle of advance, 31°, −2°, 122°, 149°, 329°. **7.** $\frac{3}{2}$; $\frac{9}{5}$. **8.** 297·8. **9.** Cylinder diameter, 30 in.; stroke, 5 ft. **10.** 50·5 lbs. per sq. in. **11.** 0·15 in. **12.** 14·31 in.; 40, assuming efficiency of 80 per cent.

Twelfth Set

1. 9·33. **3.** 72·1 lbs. per sq. in. **4.** 8·137. **5.** 67·8. **6.** 54·24. **7.** Mean effective pressure, 95 lbs. per sq. in.; indicated horse-power, 12·42; thermal efficiency, 25·22 per cent. **8.** (*a*) 8·75 per cent.; (*b*) 20·9 per cent.; (*c*) 22·96 per cent.

INDEX

A

Absolute zero, 150
Absorptive power, 172
Acceleration, 9
— uniform, 9
Addendum circle, 48
Angular acceleration, 26
— velocity, 25
Annealing, 112
Archimedes, 121
Atom, 180
Atomic weight, 181
Average speed, 3
Avogadro's Law, 181

B

Bearings, 82
Boiler fittings, 202
— inspection, 202
Bow's notation, 53, 65
Boyle's Law, 146, 218
Brake horse-power, 219
Brass, 113
Brinell test, 110
Brittleness, 111
Bronze, 113

C

Callendar's apparatus, 168
Cam, 92
Caloric, 133
Calorie, 155
Calorific value, 164
Cast iron, 112
Celsius, 133
Centre of area, 60
— of buoyancy, 122
— of gravity, 53, 60
— of mass, 60
— of pressure, 119
Centrifugal force, 29, 230
Centripetal force, 29
Charles's Law, 147
C.H.U., 155
Clerk cycle, 245
Coefficient of contraction, 129
— of discharge, 129
— of expansion, 138
— of friction, 74
— of velocity, 129
Cohesion, 104, 116
Combustion, 180
Compound engines, 224
Conduction, 174
Conductivity, 176
Convection, 174
Crank and connecting rod, 87
Cushion steam, 211
Cylinder condensation, 223

D

Davy, 133
— safety lamp, 175
De Laval steam turbine, 228
Density, 123
Diagram factor, 218
Diesel cycle, 247
Dryness fraction, 163
Ductility, 111

E

Eccentricity of valve, 213
Efficiency, 95, 185, 220
Elastic limit, 106
Element, 180
Emissivity, 172
Energy, 41
— conservation of, 41
— transmission, 44
Engineering materials, 112
Equilibrant, 59
Equivalent evaporation, 186

F

Factor of safety, 109
Fahrenheit, 133
Flash point, 81
Fletcher trolley, 15, 22
Force, 20, 37
— diagram, 65
— representation, 53
Framed structures, 65
Friction, 73, 99

G

Galileo, 133
Geometry of motion, 1
Graphic statics, 65

H

Hardness, 110
Helium, 150
Hooke's Law, 108
Hunting, 212
Hydrometer, 127

I

Ideal machine, 99
Impact, 24
Impulse, 23
Indicated horse-power, 219, 241
Indicator, 216
— diagram errors, 221
Inertia, 20

J

Joule, 133, 168
Junction valve, 203

K

Kinematics, 1
Kinetics, 20

L

Lacquer, 113
Lap of a slide valve, 213
Latent heat, 160, 183
Law of pressure, 149
Laws of motion, 25
Lead of a slide valve, 213
Lever, 85
Lewis Thompson calorimeter, 164
Like forces, 57
Link polygon, 68
Louvre stoker, 191

M

Machine, 85
Mass, 21
Maxwell, 181
Mean effort, 39
Mechanical advantage, 95
— equivalent of heat, 168
— stokers, 187
Mechanism, 85
Metacentre, 122
Methods of stoking, 185
Molecule, 104, 133, 180
Moment of a force, 55

N

Newcomen, 209
Newton, 24
Non-parallel forces, 60

O

Oils, classification of, 81
Orifice, 128
Otto cycle, 236

P

Papin, 209
Parallel forces, 54
— — theory of, 58
Parallelogram of accelerations, 7
— of forces, 7
— of velocities, 7
Parsons turbine, 230
Permanent set, 107
Pitch circle, 48
Polygon of forces, 64
Power, 43
Pressure at a point, 116

R

Radian, 25
Radiation, 172
Raymond-Lopulco mill, 189
Regnault, 141
Relative velocity, 6
Restitution, coefficient of, 24
Resultant, 59
Root circle, 49
Rumford, 133

S

Sensible heat, 163
Simmance-Abady calorimeter, 166
Simple harmonic motion, 32
Space-time curve, 1
Specific gravity, 123, 125, 126
— heat, 155
Spectrum, 172
Speed, 3
Steel, 113
Strain, 108
Strength, 110
Stress, 108
Structure diagram, 65
Suction gas producer, 241
Supercharging, 247
Superelevation of railway lines, 30
Superheated steam, 163, 224

T

Temperature, 133
— coefficient, 138
— gradient, 176
Theory of Exchanges, 173
Thermal conductivity, 176
Timber, 113
Total heat, 163
Travel of a slide valve, 213
Turbulence, 188

U

Ultimate strength, 109
Uniflow engine, 226
Uniform velocity, 3
Units of force, 20, 21
Unlike forces, 58

V

Vector, 3, 27
Velocity, 3
— ratio, 95
Velocity time curve, 10, 12, 13, 14
Viscosity, 81

W

Water equivalent, 157
— hammer, 203
Watt, 209
— governor, 212
Wave motion, 172
Weight, 21
— thermometer, 143
Weston's differential pulley, 97
White metal, 113
Wire drawing, 222
Work, 37
— graphical representation of, 39
Wrought iron, 113

X

X-rays, 173

Y

Yield point, 107
Young's modulus, 108

Z

Zeppelins, 150

Printed in Great Britain at The Darien Press, *Edinburgh*

A SELECTION OF IMPORTANT WORKS

FROM

THE TECHNICAL PRESS LIST

Engineering Workshop Manual

For Fitters, Turners, and General Machinists. Containing practical Information on the Micrometer, Vernier, Tools, Screw-Cutting, Workshop Arithmetic, Geometry, Mensuration, Gear-Cutting, and General Machine Work. With Notes, Rules, and Tables. Sixth Edition, Revised and Enlarged, of "The Engineering Workshop Handbook." New Impression. By E. PULL, M.I.Mech.E., M.I.Mar.E. Crown 8vo, cloth. 190 pages, with 140 Illustrations and numerous Tables *Net* **2s. 6d.**

Works Manager's Handbook

Comprising Modern Rules, Tables, and Data. For Engineers, Millwrights, and Boiler Makers; Toolmakers, Machinists, and Metal Workers; Iron and Brass Founders, &c. By W. S. HUTTON, Civil and Mechanical Engineer, Author of "The Practical Engineer's Handbook." Eighth Edition, carefully Revised. Medium 8vo, strongly bound ... ... *Net* **18s.**

The Young Engineer

With particular reference to Indian practice. By J. N. NIGUES LA TOUCHE. 256 pp. Illus. Cr. 8vo. ... ... *Net* **5s.**

Engineering Workshop Notes and Data

Containing a Selection of Practical Notes, Formulæ, and Data, based on Modern Methods and applicable to all branches of Engineering Workshop Practice. By ERNEST PULL, R.N.R., M.I.Mech.E., M.I.Mar.E., author of "Modern Workshop Practice," Inspector and Lecturer at the London County Council School of Engineering, Poplar; and F. E. PULL, A.I.Mar.E. 128 pages. Pott 16mo, limp ... ... *Net* **2s. 6d.**

Engineers' Measuring Tools

The Construction and Use of Modern Tool-Room Appliances. By ERNEST E. PULL, M.I.Mech.E., &c., &c. Crown 8vo, about 120 pages, with numerous Illustrations ... ... *Net* **4s. 6d.**

Milling Machines

Their Design, Construction, and Working. A Handbook for Practical Men and Engineering Students. By JOSEPH HORNER, A.M.I.Mech.E., Author of "Pattern Making," &c. With 269 Illustrations. Medium 8vo, cloth ... ... *Net* **15s.**

Screw Cutting for Engineers

A Handbook for Practical Mechanics and Technical Students. By Ernest Pull, M.I.Mech.E., M.I.M.E. Second Edition. 88 pages. Illustrated. Crown 8vo, cloth ... *Net* **2s. 6d.**

Gears and Gear-cutting

Based on "Toothed Gearing," by Joseph Horner, A.M.I.M.E. Revised and brought up to date by Philip Gates, late Lecturer in Machine Construction and Drawing, Aylesbury Technical School. 148 pages. 76 Illustrations. 10 Tables. Crown 8vo, cloth ... ... *Net* **5s.**

Principles—Spur Gearing—Bevel Gears—Worms and Worm Wheels—Helical Gearing—Spiral Gears—Skew Bevels—The Odontograph—Proportion of Wheels.

Mass Production Equipment

Covering the Design of "Jigs, Tools, and Fixtures," and Equipment for practically all Modern Machine Tools. By Philip Gates, Lecturer, Aylesbury Technical School. 220 pages. 168 Illustrations. 22 Tables. Crown 8vo, cloth ... *Net* **7s. 6d.**

Mechanical Drawing—Sketching—First Considerations in the Design of Jigs, Tools, and Fixtures—Drill Jigs—Milling Fixtures—Chucks and Turning Equipment—Cutters—Screwing Equipment—Gauges—Press Tools—Brown and Sharp Cams—Special Equipment—Jig and Tool Office Procedure—Standardization—Magnetic and Pneumatic Gripping.

Punches, Dies, and Tools for Manufacturing in Presses

By Joseph V. Woodworth. Fourth Enlarged Edition. 538 pages, with 736 Illustrations. Medium 8vo, cloth ... *Net* **25s.**

Special Sections illustrating and explaining the making of Cartridge Shells, Wire and Steel Drawing Dies—Press Tools for making Hydraulic Leather Packing—The making of Paint and Chemical Tablets, Manufacture of Pens, Pins, Needles—Jewellery and Eye-Glass Die-Making—Spoon and Fork-Making Dies—Sub-Press Die-Making for Watch and Clock Work—Drop Dies, Drop Forging, and Ornamental Die-Making.

Steam Power Stations.

Equipment and Maintenance. By G. O. M'Lean, M.Eng. (Liverpool), A.M.I.E.E. 112 pages. 4 plates. Crown 8vo, cloth ... ... *Net* **7s. 6d.**

Boiler-Making and Plating

A Practical Handbook for Workshop Operations, including an Appendix of Tables. By J. G. Horner, A.M.I.Mech.E. Third Edition. With upwards of 300 Illustrations. Large crown 8vo, cloth ... ... *Net* **12s. 6d.**

Boilermaker's Assistant

In Drawing, Templating, and Calculating Boiler Work and Tank Work, &c. With Rules for Safety Valves, and useful Tables of Rivet Joints, of Circles, Weights of Metals, Materials of Construction, &c. By J. Courtney, Revised by Lieut.-Commander G. C. Malden, R.N., Lecturer in Metallurgy, Royal Naval College, Keyham. 110 pp., Illustrated. Crown 8vo, cloth ... ... *Net* **2s. 6d.**

From the Technical Press List

Brass Founders' and Finishers' Manual

By PHILIP GATES, late Lecturer in Machine Construction, Aylesbury Technical School. 180 pp., 56 Illus. Crown 8vo, cloth ... ... *Net* 5s.

PATTERN-MAKING—ALLOYS—FOUNDRY WORK—CLEANING CASTINGS—BRASS FINISHING—SURFACE FINISHING—CLEANING BRASS—OLD LACQUER—POLISHING AND BURNISHING—BRONZING AND LACQUERING—SOLDERING.

Pattern Making

Embracing the Main Types of Engineering Construction, and including Gearing, Engine Work, Sheaves and Pulleys, Pipes and Columns, Screws, Machine Parts, Pumps and Cocks, the Moulding of Patterns in Loam and Greensand, together with the Methods of Estimating the Weight of Castings, and an Appendix of Tables for Workshop Reference, &c. By J. G. HORNER, A.M.I.M.E. Fifth Edition, thoroughly Revised and much Enlarged. 450 pages. Over 600 Illustrations. Demy 8vo, cloth *Net* 18s.

Lathe Work

A Practical Treatise on the Tools, Appliances, and Processes employed in the Art of Turning. By PAUL N. HASLUCK. Eleventh Edition, Revised and Enlarged, with chapters on Turret and Capstan Lathes. 240 pp. Illustrated. Crown 8vo, cloth. Re-Issue ... . *Net* 5s.

The Strength of Shafts in Vibration

By Captain J. MORRIS, B.A., A.F.R.Ae.S. (late R.A.F.). Formerly Scholar of Corpus Christi College, Cambridge. 200 pp., illustrated. Crown 4to, cloth ... ... *Net* 30s.

Liquid Fuels

Their Manufacture, Properties, Utilisation, and Analysis. A Practical Treatise for Engineers and Chemists. By HAROLD MOORE, M.Sc.Tech., F.C.S., M.I.P.T., A.I.Mech.Eng. 272 pages, copiously illustrated by Diagrams. Charts, Graphs, and Tables. Demy 8vo, cloth ... ... *Net* 21s.

Slide Rule, and How to Use it

By CHARLES HOARE, C.E. With a Slide Rule in tuck of cover. Fourteenth Im. Cr. 8vo, cloth ... ... *Net* 4s.

Workshop Practice

A Practical Text-Book for the use of Engineers, Apprentices, and Students in Technical Institutes. A revised and enlarged edition of E. Pull's "Modern Workshop Practice." By F. JOHNSTONE TAYLOR. 780 pages. Over 542 Illustrations. Crown 8vo, cloth ... ... *Net* 16s.

A wealth of information comprising all branches of Engineering Workshop Practice.

Adopted as a text-book by many important Educational Authorities.

A Selection of Books

Blacksmith's Manual Illustrated

By J. W. Lillico, Practical Blacksmith and ex-Foreman (Scotswood Works of Sir W. G. Armstrong, Whitworth & Co. Ltd.). A Practical Treatise on modern methods of production, for Blacksmiths, Apprentice Blacksmiths, Engineers and others. 220 pp. 100 Plates, containing 755 perspective illustrations. Royal 8vo, cloth ... ... *Net* **9s.**

Introduction—Description of Forges and Hearths—Uses of Hand Tools—Anvil Tools—Power Hammer Tools—Angle Bar Tools—Formulæ for Obtaining the Length of Forgings—Links—Shackles—Clams—Angle Bar Rings—Stamp Making—Stamp Forging—Locomotive Forging—Hardening and Tempering—Colour Tables—Miscellaneous Examples of Forged Work in Different Stages.

The Mechanical Transmission of Power

By Professor G. F. Charnock, Member of Council, I.Mech.E. 176 pages. Demy 8vo, cloth. Illustrated ... *Net* **8s. 6d.**

Introduction—Shafting—Bearings for Line Shafting—Belt Driving—Types of Pulleys—Roof Driving—Chain Driving—Toothed Gearing—Friction Clutches for Power Transmission—Variable Speed Transmission.

Heat Treatment in Forging Steel

A Manual on the Application of Science to the Heating, Cooling, and Forging of Steel. By B. Saunders. 128 pages. 38 Illustrations. Crown 8vo, cloth ... ... *Net* **5s.**

Preparation of Steels—Handling—Case-Hardening—Welding—Testing—Furnaces—Temperature Measurements and Pyrometers—Calculating—Definitions of some Terms used in Treatment of Steel—Index.

Mechanical Handling and Storing of Material

A Treatise on the Automatic and Semi-Automatic Handling and Storing of Commercial Products. Fourth Edition. Enlarged. By George Frederick Zimmer, A.M.Inst.C.E. In Two Volumes. 912 pages, with 1,253 Illustrations (including numerous Folding Plates) specially prepared for the Work. Super royal 8vo, cloth ... ... *Net* **£3. 3s.**

LONDON

THE TECHNICAL PRESS LTD

5 AVE MARIA LANE, LUDGATE HILL, E.C.4

DATE OF ISSUE

1 AUG [illegible]

This book must be returned within 3, 7, 14 days of its issue. A fine of ONE ANNA per day will be charged if the book is overdue.

Class No. 620:7 Book No. H14F
Vol.

Author Hall
Title Foundations for the Study of Engg.
Acc No. 45366

21 Se'59 P/64
27 Oc'59 2441